GUIDANCE, NAVIGATION, AND CONTROL 2020

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Image: Checkpoint-Rehearsal-Movie-1024x720.gif
Caption: “OSIRIS-REx Buzzes Sample Site Nightingale”
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Frontispiece Illustration:

Image: NASA_Orion_EarthRise.jpg
Caption: “Orion Primed for Deep Space Exploration”
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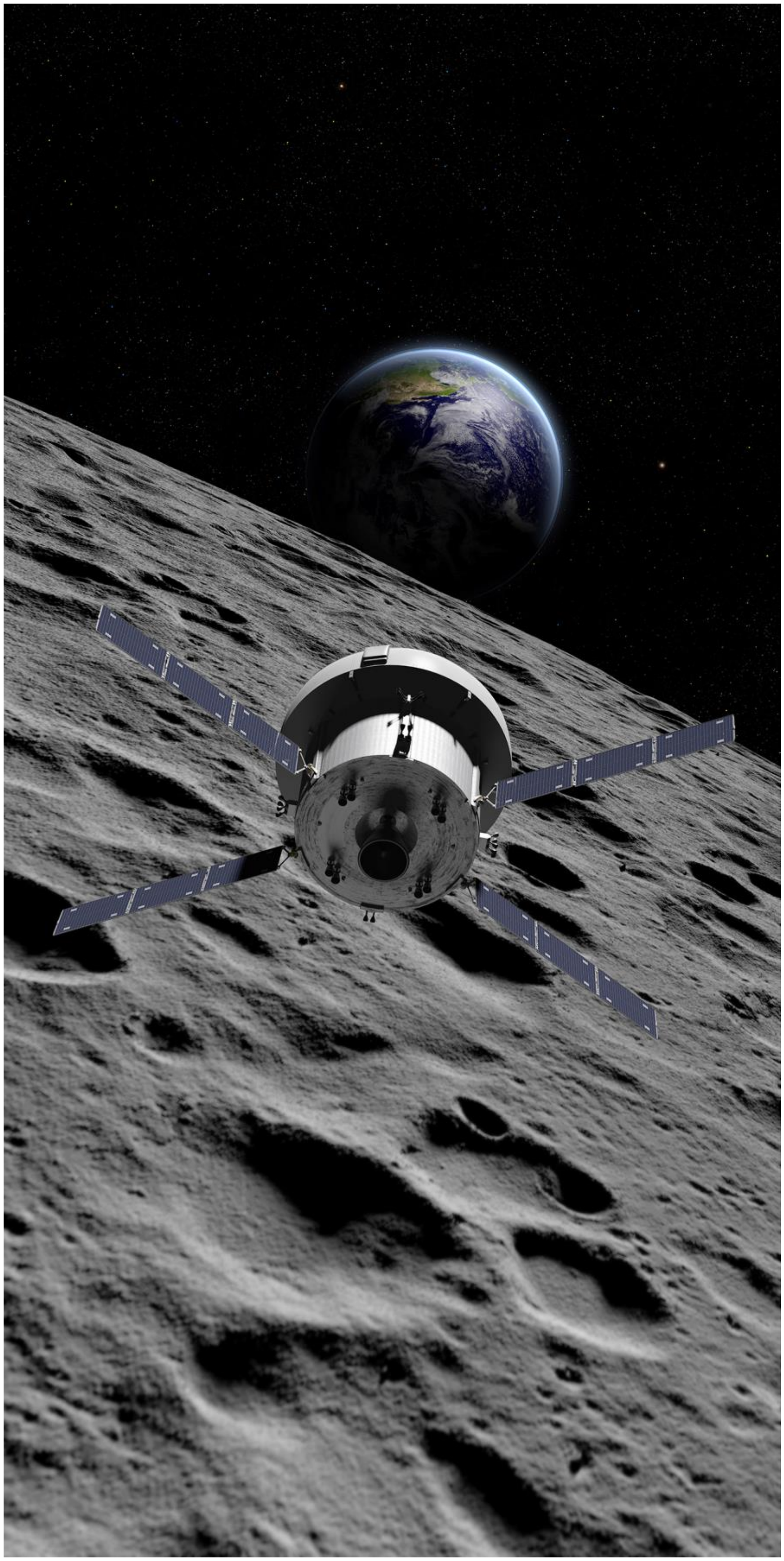

GUIDANCE, NAVIGATION, AND CONTROL 2020

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Edited by
Jastesh Sud

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FOREWORD

HISTORICAL SUMMARY

The annual American Astronautical Society Rocky Mountain Guidance, Navigation and Control Conference began as an informal exchange of ideas and reports of achievements among local guidance and control specialists. Since most area guidance and control experts participate in the American Astronautical Society, it was natural to gather under the auspices of the Rocky Mountain Section of the AAS.

In the late seventies, Bud Gates, Don Parsons and Sherm Seltzer jointly came up with the idea of convening a broad spectrum of experts in the field for a fertile exchange of aerospace control ideas. At about this same time, Dan DeBra and Lou Herman had discussed a similar plan.

Bud and Don approached the AAS Section Chair, Bob Culp, with their proposal. In 1977, Bud Gates, Don Parsons, and Bob Culp organized the first conference, and began the annual series of meetings the following winter. Dan and Lou were delighted to see their concept brought to reality and joined enthusiastically from afar. In March 1978, the First Annual Rocky Mountain Guidance and Control Conference met at Keystone, Colorado. It met there for eighteen years, moving to Breckenridge in 1996 where it has been for almost 25 years. The 2020 Conference was the 43rd Annual AAS Rocky Mountain Guidance, Navigation and Control Conference.

There were thirteen members of the original founders. The first Conference Chair was Bud Gates, the Co-Chair was Section Chair Bob Culp, with the arrangements with Keystone by Don Parsons. The local session chairs were Bob Barsocchi, Carl Henrikson, and Lou Morine. National session chairs were Sherm Seltzer, Pete Kurzhals, Ken Russ, and Lou Herman. The other members of the original organizing committee were Ed Euler, Joe Spencer, and Tom Spencer. Dan DeBra gave the first tutorial.

The style was established at the first Conference, strictly adhered to until 2013, involved no parallel sessions and two three-hour technical/tutorial sessions. For the first fifteen Conferences, the weekend was filled with a tutorial from a distinguished researcher from academia. The Conferences developed a reputation for concentrated, productive work.

After the 2012 conference, it was clear that overall industry budget cuts were leading to reduced attendance and support. In an effort to meet the needs of the constituents, parallel conference sessions were added for 3 of the 8 sessions on a trial basis during the 2013 conference. The success of the parallel sessions was carried forward and expanded. In 2020, to accommodate the increased interest and diversity of papers, the concept of parallel sessions was extended further by the introduction of parallel triple tracks.

A tradition from the beginning and retained until 2014 had been the Conference banquet. A general interest speaker was a popular feature. The banquet speakers included:

Banquet Speakers

1978 Sherm Seltzer, NASA MSFC, told a joke
1979 Sherm Seltzer, Control Dynamics, told another joke
1980 Andrew J. Stofan, NASA Headquarters, "Recent Discoveries through Planetary Exploration."
1981 Jerry Waldvogel, Cornell University, "Mysteries of Animal Navigation."
1982 Robert Crippen, NASA Astronaut, "Flying the Space Shuttle."
1983 James E. Oberg, author, "Sleuthing the Soviet Space Program."
1984 W. J. Boyne, Smithsonian Aerospace Museum, "Preservation of American Aerospace Heritage: A Status on the National Aerospace Museum."

1985 James B. Irwin, NASA Astronaut (retired), "In Search of Noah's Ark."
1986 Roy Garstang, University of Colorado, "Halley's Comet."
1987 Kathryn Sullivan, NASA Astronaut, "Pioneering the Space Frontier."
1988 William E. Kelley and Dan Koblosh, Northrop Aircraft Division, "The Second Best Job in the World, the Filming of Top Gun."
1989 Brig. Gen. Robert Stewart, U.S. Army Strategic Defense Command, "Exploration in Space: A Soldier-Astronaut's Perspective."
1990 Robert Truax, Truax Engineering, "The Good Old Days of Rocketry."
1991 Rear Admiral Thomas Betterton, Space and Naval Warfare Systems Command, "Space Technology: Respond to the Future Maritime Environment."
1992 Jerry Waldvogel, Clemson University, "On Getting There from Here: A Survey of Animal Orientation and Homing."
1993 Nicholas Johnson, Kaman Sciences, "The Soviet Manned Lunar Program."
1994 Steve Saunders, JPL, "Venus: Land of Wind and Fire."
1995 Jeffrey Hoffman, NASA Astronaut, "How We Fixed the Hubble Space Telescope."
1996 William J. O'Neil, Galileo Project Manager, JPL, "PROJECT GALILEO: JUPITER AT LAST! Amazing Journey—Triumphant Arrival."
1997 Robert Legato, Digital Domain, "Animation of Apollo 13."
1998 Jeffrey Harris, Space Imaging, "Information: The Defining Element for Superpowers-Companies & Governments."
1999 Robert Mitchell, Jet Propulsion Laboratories, "Mission to Saturn."
2000 Dr. Richard Zurek, JPL, "Exploring the Climate of Mars: Mars Polar Lander in the Land of the Midnight Sun."
2001 Dr. Donald C. Fraser, Photonics Center, Boston University, "The Future of Light."
2002 Bradford W. Parkinson, Stanford University, "GPS: National Dependence and the Robustness Imperative."
2003 Bill Gregory, Honeywell Corporation, "Mission STS-67, Guidance and Control from an Astronaut's Point of View."
2004 Richard Battin, MIT, "Some Funny Things Happened on the Way to the Moon."
2005 Dr. Matt Golombeck, Senior Scientist, MER Program, JPL, "Mars Science Results from the MER Rovers."
2006 Mary E. Kicza, Deputy Assistant Administrator for Satellite and Information Services, NASA, "NOAA: Observing the Earth from Top to Bottom."
2007 Patrick Moore, Consulting Senior Life Scientist, SAIC and the Navy Marine Mammal Program, "Echolocating Dolphins in the U.S. Navy Marine Mammal Program."
2008 Dr. Ed Hoffman, Director, NASA Academy of Program and Project Leadership, "The Next 50 Years at NASA – Achieving Excellence."
2009 William Pomerantz, Senior Director for Space, The X Prize Foundation, "The Lunar X Prize."
2010 Berrien Moore, Executive Director, Climate Central, "Climate Change and Earth."
2011 Joe Tanner, Former Astronaut; Senior Instructor, University of Colorado, "Building Large Objects in Space."
2012 Greg Chamitoff, Ph.D., NASA Astronaut, "Completing Construction of the International Space Station — The Last Mission of Space Shuttle Endeavour."
2013 Thomas J. "Dr. Colorado" Noel, Ph.D., Professor of History and Director of Public History, Preservation & Colorado Studies at University of Colorado Denver, "Welcome to the Highest State: A Quick History of Colorado."

For 2014 a change was made to replace the banquet dinner with a less formal social networking event where conference attendees would have a designated time and venue to encourage building relations. The keynote speaker event of the evening was retained and provided stimulating discussion and entertainment in 2014. Subsequent years retained the networking event but eliminated the speaker in favor of more time to interact with other conference attendees.

2014 Neil Dennehy, Goddard Space Flight Center and Stephen "Phil" Airey, European Space Agency, "Issues Concerning the GN&C Community."

In addition to providing for an annual exchange of the most recent advances in research and technology of astronautical guidance and control, for the first fourteen years the Conference featured a full-day tutorial in a specific area of current interest and value to the guidance and control experts attending. The tutor was an academic or researcher of special prominence in the field. These lecturers and their topics were:

Tutorials

1978 Professor Dan DeBra, Stanford University, "Navigation"
1979 Professor William L. Brogan, University of Nebraska, "Kalman Filters Demystified"
1980 Professor J. David Powell, Stanford University, "Digital Control"
1981 Professor Richard H. Battin, Massachusetts Institute of Technology, "Astrodynamics: A New Look at Old Problems"
1982 Professor Robert E. Skelton, Purdue University, "Interactions of Dynamics and Control"
1983 Professor Arthur E. Bryson, Stanford University, "Attitude Stability and Control of Spacecraft"
1984 Dr. William B. Gevarter, NASA Ames, "Artificial Intelligence and Intelligent Robots"
1985 Dr. Nathaniel B. Nichols, The Aerospace Corporation, "Classical Control Theory"
1986 Dr. W. G. Stephenson, Science Applications International Corporation, "Optics in Control Systems"
1987 Professor Dan DeBra, Stanford University, "Guidance and Control: Evolution of Spacecraft Hardware"
1988 Professor Arthur E. Bryson, Stanford University, "Software Application Tools for Modern Controller Development and Analysis"
1989 Professor John L. Junkins, Texas A&M University, "Practical Applications of Modern State Space Analysis in Spacecraft Dynamics, Estimation and Control"
1990 Professor Laurence Young, Massachusetts Institute of Technology, Aerospace Human Factors"
1991 The Low-Earth Orbit Space Environment
Professor G. W. Rosborough, University of Colorado, "Gravity Models"
Professor Ray G. Roble, University of Colorado, "Atmospheric Drag"
Professor Robert D. Culp, University of Colorado, "Orbital Debris"
Dr. James C. Ritter, Naval Research Laboratory, "Radiation"
Dr. Gary Heckman, NOAA, "Magnetics"
Dr. William H. Kinard, NASA Langley, "Atomic Oxygen."

Since 1991, the conference has featured a mix of tutorials, technical workshops, and special sessions as focal points. In 1992 the theme was "Mission to Planet Earth" with presentations on all the large Earth Observer programs. In 1993 the feature was "Applications of Modern Control: Hubble Space Telescope Performance Enhancement Study" organized by Angie Bukley of NASA Marshall. In 1994 Jason Speyer of UCLA discussed "Approximate Optimal Guidance for Aerospace Systems." In 1995 a special session on "International Space Programs" featured programs from Canada, Japan, Europe, and South America. In 1996, and again in 1997, one of the most popular features was Professor Juris Vagners, of the University of Washington with "A Control Systems Engineer Examines the Biomechanics of Snow Skiing." In 2005, Angie Bukley chaired a tutorial session "University Work on Precision Pointing and Geolocation." In 2006, a special day for U.S. citizens only was inserted at the beginning of the Conference to allow for topics that were limited due to ITAR constraints. In 2007, two special invited sessions were held: "Lunar Ambitions—The Next Generation" and "Project Orion—The Crew Exploration Vehicle." In 2008, a special panel addressed "G&C Challenges in the Next 50 Years." The 2009 Conference featured a special session on "Constellation Guidance, Navigation, and Control." In 2013, the nail-biting but successful landing of Curiosity on Mars inspired a special session on "Entry, Descent and Landing Flight Dynamics." In 2015 and 2017 the Orion capsule development resulted in special sessions on the GN&C aspects of capsule design. In 2017 the extensive list of technology demonstration missions performed in Europe inspired a session on "European ger two very interesting and relevant sessions. In 2020, recent deep space exploration missions by NASA and other international space agencies featuring asteroid exploration inspired a session on “Asteroid Exploration and Small Body Sample Return.” Also, the variety of efforts related to Human Spaceflight motivated a focused session on “Human Spaceflight and Deep Space Gateway.”

From the beginning, the Conference has provided extensive support for students interested in aerospace guidance and control. The Section, using proceeds from this Conference, annually gives $2,000 in the form of scholarships at the University of Colorado, one to the top Aerospace Engineering Sciences senior, and one to an outstanding Electrical and Computer Engineering senior, who has an interest in aerospace guidance and control. The Section has assured the continuation of these scholarships in perpetuity through an $85,000 endowment. The Section supports other space education through grants to K-12 classes throughout the Section at a rate of over $10,000 per year. All this is made possible by this Conference.

The student scholarship winners attend the Conference as guests of the American Astronautical Society and are presented with scholarship plaques. These scholarship winners have gone on to significant success in the industry.

Scholarship Winners

	Aerospace Engineering Sciences	Electrical and Computer Engineering
1981	Jim Chapel	
1982	Eric Seale	
1983	Doug Stoner,	John Mallon
1984	Mike Baldwin,	Paul Dassow
1985	Bruce Haines,	Steve Piche
1986	Beth Swickard,	Mike Clark
1987	Tony Cetuk,	Fred Ziel
1988	Mike Mundt,	Brian Olson
1989	Keith Wilkins,	Jon Lutz
1990	Robert Taylor,	Greg Reinacker
1991	Jeff Goss,	Mark Ortega
1992	Mike Goodner,	Dan Smathers
1993	Mark Baski,	George Letey
1994	Chris Jensen,	Curt Musfeldt
1995	Mike Jones,	Curt Musfeldt
1996	Karrin Borchard,	Kirk Hermann
1997	Tim Rood,	Ui Han
1998	Erica Lieb,	Kris Reed
1999	Trent Yang,	Adam Greengard
2000	Josh Wells,	Catherine Allen
2001	Justin Mages,	Ryan Avery
2002	Tara Klima,	Kiran Murthy
2003	Stephen Russell,	Andrew White
2004	Trannon Mosher,	Negar Ehsan
2005	Matt Edwards,	Henry Romero
2006	Arseny Dolgove,	Henry Romero
2007	Kirk Nichols,	Chris Aiken
2008	Nicholas Hoffmann,	Gregory Stahl
2009	Filip Maksimovic,	Justin Clark
2010	John Jakes,	Filip Maksimovic
2011	Weceslao Shaw-Cortez Jr.,	Andrew Tomas
2012	Jacob Hynes,	Nicholas Mati
2013	Kirstyn Johnson,	Caitlyn Cooke
2014	David Thomas,	John Kablubowski

2015	Esteban Rodriguez,	Ryan Montoya
2016	Ryan Montoya,	Esteben Rodriguez
2017	Alec Weiss,	Matthew Hurst
2018	Marika Schubert,	Ryan Aronson
2019	Jacob Melonis,	Cody Goldman
2020	Jarrod Puseman,	Ryan Nickles

In 2013, in an effort to increase student involvement, a special *Student Paper Session* was added to the program. This session embraces the wealth of research and innovative projects related to spacecraft GN&C being accomplished in the university setting. Papers in this session require a student as the primary author and presenter, and address hardware and software research as well as component, system, or simulation advances. Papers are adjudicated based on level of innovation, applicability and fieldability to near-term systems, clarity of written and verbal delivery, number of completed years of schooling and adherence to delivery schedule.

Student Paper Winners

2013 1st Place: Nicholas Truesdale, Kevin Dinkel, Jedediah Diller, Zachary Dischnew, "Daystar: Modeling and Testing a Daytime Star Tracker for High Altitude Balloon Observatories"

2nd Place: Christopher M. Pong, Kuo-Chia Liu, David W. Miller, "Angular Rate Estimation from Geomagnetic Field Measurements and Observability Singularity Avoidance during Detumbling and Sun Acquisition"

3rd Place: Gregory Eslinger, "Electromagnetic Formation Flight Control Using Dynamic Programming"

2014 1st Place: Dylan Conway, Brent Macomber, Kurt A. Cavalieri, John L. Junkins, "Vision-Based Relative Navigation Filter for Asteroid Rendezvous"

2nd Place: Robyn M. Woollands, John L. Junkins, "A New Solution for the General Lambert Problem"

3rd Place: Alex Perez, "Closed-Loop GN&C Linear Covariance Analysis for Mission Safety"

2015 1st Place: Andrew Liounis, Alexander Entrekin, Josh Gerhard, John Christian, "Performance Assessment of Horizon-Based Optical Navigation Techniques"

2nd Place: J. Micah Fry, "Aerodynamic Passive Attitude Control: A New Approach to Attitude Propagation and a Nano-satellite Application"

3rd Place: Siamak Hesar, Jeffrey S. Parker, Jay McMahon, George H. Born, "Small Body Gravity Field Estimation Using Liaison Supplemented Optical Navigation"

2016 1st Place: Brian C. Fields, Shawn M. Kocis, Kerri L. Williams, and Mark Karpenko, "Hardware-in-the-Loop Simulator for Rapid Prototyping of CMG-Based Attitude Control Systems."

2nd Place: Ann Dietrich and Jay W. McMahon, "Error Sensitivities for Flash LIDAR Based Relative Navigation around Small Bodies"

3rd Place: Kevin D. Anderson, Darryll J. Pines, and Suneel I. Sheikh, "Investigation of Combining X-ray Pulsar Phase Tracking Estimates to Form a 3D Trajectory"

2017 1st Place: Simon Shuster, Andrew J. Sinclair, and T. Alan Lovell, "Uncertainty Analysis for Initial Relative Orbit Determination Using Time Difference of Arrival Measurements"

2nd Place: Himangshu Kalita, Ravi Teja Nallapu, Andrew Warren, and Jekan Thangavelautham, "Guidance, Navigation and Control of Multirobot Systems in Cooperative Cliff Climbing"

3rd Place: Max Rogovin and Brian Kester, "Two-Axis Stability of a High-Altitude Balloon Payload"

2018 1st Place: F. Franquiz, B. Udrea, M. Balas, "Optimal Rate Observability Trajectory Planning For Proximity Operations Using Angles-Only Navigation"

2nd Place: B. Bercovici, J. McMahon, "Autonomous Shape Determination Using Flash-Lidar Observations and Bezier Patches"

3rd Place: D. Jennings, J. Davis, P. Galchenko, H. Pernicka, "Validation of a GNC Algorithm Using a Stereoscopic Imaging Sensor to Conduct Close Proximity Operations"

2019 1st Place: A. Reynolds and H. Pernicka "Design and Verification of a Stereoscopic Imager for Use in Spacecraft Close Proximity Operations."

2nd Place: A. Boylston, J. Gaebler, and P. Axelrad "Extracting CubeSat Relative Motion Using In Situ Deployment Imagery"

3rd Place: G. Willburn, H. Kalita, A. Chandra, S. Schwartz, E. Asphaug, and J. Thangavelautham "Guidance Navigation and Control of Asteroid Mobile Imager and Geologic Observer (AMIGO)"

2020 1st Place: Lindsey A. Marinello and John Y. Liu "Investigation of Prandtl-Ishlinskii Hysteresis Compensation for Deep Space Optical Communications Pointing Control"

2nd Place: Kenshiro Oguri and Jay W. McMahon "Autonomous Guidance for Robust Achievement of Science Observations Around Small Bodies"

3rd Place: Vishala Arya, Ehsan Taheri and John L. Junkins "A Composite Framework for Joint Optimization of Trajectory and Propulsion System Design"

In 2015 the AAS Rocky Mountain Section partnered with the University of Colorado and hosted the inaugural STEM SCAPE conference on Saturday, which provided an introduction for the students to working in a STEM field and motivated them to pursue professional careers in aerospace engineering. This highly successful session brought in high school students, college students and included a design project, panel discussions, an opportunity to meet industry representatives, practice interviews for the college students and a keynote speech. The success of this event has been carried forward and expanded to reach well over 100 high school and college students in 2020.

The Rocky Mountain Section of the American Astronautical Society established the Rocky Mountain Guidance and Control Committee, chaired *ex-officio* by the next Conference Chair, to prepare and run the annual Conference. The Conference, now named the AAS Guidance, Navigation and Control Conference, and sponsored by the national AAS, annually attracts about 200 of the nation's top specialists in space guidance, navigation and control.

	Conference Chair	Attendance
1978	Robert L. Gates	83
1979	Robert D. Culp	109
1980	Louis L. Morine	130
1981	Carl Henrikson	150
1982	W. Edwin Dorroh, Jr.	180
1983	Zubin Emsley	192
1984	Parker S. Stafford	203
1985	Charles A. Cullian	200
1986	John C. Durrett	186
1987	Terry Kelly	201
1988	Paul Shattuck	244
1989	Robert A. Lewis	201
1990	Arlo Gravseth	254
1991	James McQuerry	256
1992	Dick Zietz	258
1993	George Bickley	220
1994	Ron Rausch	182
1995	Jim Medbery	169
1996	Marv Odefey	186
1997	Stuart Wiens	192
1998	David Igli	189
1999	Doug Wiemer	188
2000	Eileen Dukes	199
2001	Charlie Schira	189

2002	Steve Jolly	151
2003	Ian Gravseth	178
2004	Jim Chapel	137
2005	Bill Frazier	140
2006	Steve Jolly	182
2007	Heidi Hallowell	206
2008	Michael Drews	189
2009	Ed Friedman	160
2010	Shawn McQuerry	189
2011	Kyle Miller	161
2012	Michael Osborne	139
2013	Lisa Hardaway	181
2014	Alexader May	180
2015	Ian Granvseth	195
2016	David Chart	216
2017	Reuben Rohrschneider	201
2018	Cheryl Walker	236
2019	Heidi Hallowell	215
2020	Jastesh Sud	253

The AAS Guidance, Navigation and Control Technical Committee, with its national representation, provides oversight to the local conference committee. W. Edwin Dorroh, Jr., was the first chairman of the AAS Guidance and Control Committee; from 1985 through 1995 Bud Gates chaired the committee; from 1995 through 2000, James McQuerry chaired the committee. From 2000 through 2007, Larry Germann chaired this committee, and James McQuerry chaired the committee between 2007 and 2018. Since then Ian Gravseth has been at the helm of the Technical Steering Committee. The committee meets every year at the Conference, and also sometimes at the summer Guidance and Control Meeting, or at the fall AAS Annual Meeting.

The AAS Guidance, Navigation and Control Conference, hosted by the Rocky Mountain Section in Colorado, continues as the premier conference of its type. As a National Conference sponsored by the AAS, it promises to be the preferred idea exchange for guidance, navigation and control experts for years to come.

On behalf of the Conference Committee and the Section,

Jastesh Sud
Lockheed Martin Space
Denver, Colorado

PREFACE

The 43rd annual AAS Guidance, Navigation and Control Conference experienced significant growth compared to yesteryears. This year's conference reaped record number of papers and most ever presenters at this venue. Because of this growth and the exciting variety of topics to choose from, we introduced parallel triple tracks, which were well received by the attendees.

As always, from our first planning meeting, we strived to present the relevant topics of the day while keeping our more popular and well-attended sessions as cornerstones from year to year. Several of the topics including "Systems Engineering Impacts on GN&C Design" were directly influenced by the discussion at the Technical Steering Committee meeting at the end of the previous year's conference. We have always appreciated friends of the conference bringing those ideas to the committee and highly encourage that kind of participation. In the end, the program became a timely reflection of the current state of the space industry. We were also pleased that each session, even up to the very last one on the last morning, was well-attended. I would like to thank the planning committee for their dedication and perseverance through the ebb and flow of the planning cycle throughout the year.

Thursday and Friday featured our classified sessions held at the Aerospace Corporation in Colorado Springs. These sessions have received excellent reviews from attendees and give industry professionals the opportunity to share at a level unavailable at our traditional conference.

Our regular conference opened Saturday morning, February 1 with Session I, "Student Innovations in GN&C," a topic which has held this spot for a number of years now. It is an opportunity for students to present the latest in cutting edge research currently occurring in the academia setting. The top 3 papers, judged by a panel of conference planning committee members and attendees, were presented with awards during our Technical Exhibits session. The winners were:

<u>1st Place</u>: ***Lindsey A. Marinello*** *and John Y. Liu "Investigation of Prandtl-Ishlinskii Hysteresis Compensation for Deep Space Optical Communications Pointing Control"*

<u>2nd Place</u>: ***Kenshiro Oguri*** *and Jay W. McMahon "Autonomous Guidance for Robust Achievement of Science Observations Around Small Bodies"*

<u>3rd Place</u>: ***Vishala Arya****, Ehsan Taheri and John L. Junkins "A Composite Framework for Joint Optimization of Trajectory and Propulsion System Design"*

In parallel, the AAS STEM-Scape event, in its 5th year, gave high school students from Denver Metro and Colorado's Western Slope an opportunity to experience a professional conference as they consider their future college experiences and careers. In addition to asking questions of a panel consisting of both young professionals and those who are further along in their careers, the students also participated in a design contest. Here, they had the opportunity to put their problem-solving skills to the test in a team environment.

That evening, attendees gathered for a conference favorite – "Technical Exhibits." The diverse attendance and state-of-the-art technology exhibits present a unique setting for an informative conversation with industry, government and academia personnel over heavy hors d'oeuvres prepared by Beaver Run. This session is as much social as it is technical. As it is a family event, both young and adult attendees had the opportunity for one-on-one interaction with those in the forefront of the space industry's future.

Sunday morning featured our first ever parallel triple track sessions. Session II, "Small Satellite GN&C," opened the day with papers which highlighted a growing trend towards smaller spacecraft and commercialization of low-earth-orbit. Session III, "Advances in Hardware" gave attendees the opportunity to hear from those on the forefront of the hardware innovations which form the basis of spacecraft design. Among other things, this session featured state of the art information on LIDAR and Reaction Wheel technology innovations. Session IV, "Human Spaceflight/Deep Space Gateway" captured the renewed interest in Human Space Exploration and Boots on the Moon campaign. At the beginning of the session, Howard Hu, a program manager from NASA Johnson Space Center, provided a technology roadmap and shared NASA's vision for Human Spaceflight in deep space. The papers complemented the roadmap and highlighted the challenges associated with fielding man-rated space systems and examined the technologies that will enable deep space human exploration in the near future.

A focused poster session was held during the break Sunday morning. The assortment and quality of posters was quite amazing, which generated a healthy technical interchange between the attendees and the poster presenters.

Sunday afternoon featured Session V, "Pioneers/Technology Evolution" which was brought back by popular demand. This session offered reflections on the careers and contributions of scientists and engineers who pioneered notable technical solutions for our aerospace community. It also highlighted significant technological advances that led to historical achievements in the space industry. This session generated a lot of intrigue as the presenters took the audience on a historical journey.

Our Monday morning program consisted of another round of parallel triple track sessions. Session VI, "Advances in Propulsion," which is a mainstay for the conference, featured a wide spectrum of topics ranging from innovations in managing propellant slosh to thruster technology advancements. Session VII, "Hypersonics, Re-Entry Vehicles and EDL" focused on the status and evolutionary development of hypersonic flight, entry vehicles and entry-descent-landing (EDL). The papers highlighted novel EDL algorithms as well advancements in aerocapture capabilities for Martian entry. Lastly, Session VIII, "Asteroid Exploration/Small Body Sample Return" generated a significant interest because of the recent advancements that have been made to allow missions such as OSIRIS-REx and Hayabusa2 to operate successfully.

Monday afternoon included two short sessions in parallel. Session IX, "Systems Engineering Impacts on GN&C Design" offered insight into the symbiotic relationship between GN&C and Systems Engineering. Several examples were presented where advancements in mission analysis tools and simulations made the GN&C and system design impacts transparent. Session X, "Exploring Mars" featured a wide spectrum of papers highlighting the technological challenges associated with exploring Mars. The topics ranged from design and verification of GN&C applications for rovers, landers and EDL.

The program on Monday wrapped up with a social event. It included a first ever panel discussion on Diversity and Inclusion (D&I) at the conference, which was an unplanned addition to the agenda after the keynote speaker for the D&I event featuring "Women in Space" had to cancel at the very last minute. The entire event was re-planned that morning. In lieu of finding a backup keynote speaker, the decision was made to hold a panel discussion on the topic. A panel was formed quickly. Five highly qualified women, who were already present at the conference, volunteered to be on the panel. The courageous panel members shared their individual experiences and discussed what D&I means to them personally. The panel discussion was moderated by Melissa Sampson from Ball Aerospace and featured a Q&A session with the audience. The discussion was very lively and received head nods from audience members. It touched on several key points that are prevalent in today's society. One of the main threads was how D&I impacts the workplace culture in the Aerospace industry. In general, the event was really well received, and the dialogue provided everyone with an opportunity for retrospection.

Tuesday morning's program included two parallel sessions. Session XI, "General Advances in Guidance & Control" brought together solutions to aerospace problems that were solved using a wide variety, and various combinations, of traditional and recent advances in guidance and control theory. Session XII, "Advances in Navigation" covered innovations in processing observations from non-traditional sources to enable future lunar, interplanetary and interstellar mission concepts. Novel techniques for processing optical observations, pulsar observations and other deep space signals of opportunity were highlighted.

Tuesday afternoon featured a well-attended Beyond the Textbook Tutorial on "Machine Learning and Stochastic Control Algorithms for Safe Autonomy." Dr Evangelos Theodorou, an Associate Professor at Georgia Institute of Technology, presented advancements in the area of safe autonomy that bridge the gap between Artificial Intelligence (AI) and various optimal control, stochastic control and nonlinear optimization methods.

The program on Tuesday wrapped up with two more parallel sessions in the evening. Session XIII, "Advances in Software," a perennial favorite at the conference, featured innovations in the area of software development covering both flight software and simulation architectures. Session XIV, "Autonomous RPOD, Servicing, Collision Avoidance and Debris Removal" presented technological advancements in Navigation, Guidance and Control, Computer Vision, Robotics and Safety of Flight to support this class of missions.

The conference concluded on Wednesday with our perennially popular "Recent Experiences" session. The session featured papers highlighting the current and recently completed missions. An opportunity to hear about the trials and tribulations of flying a real mission and the lessons learned from those experiences is always a treat. This year was no exception. It was fitting that the very last paper presented at this conference was an extended discussion on Voyager spacecrafts. The Voyager spacecraft engineers and operators sowed a titillating tale that highlighted the successes, endurance, legacy and challenges of flying a mission that is in well into its fifth decade of operation.

The 43rd Annual AAS Guidance, Navigation and Control Conference was a success in all the ways the planning committee had hoped when we first began the planning process during the Spring of 2019. I could not be more proud of the dedication and perseverance that each and every member of the planning committee showed and the support they provided in making the conference a success. The conference had its mix of current hot topics and perennials which showcased the innovation occurring in GN&C. In addition, our Technical Exhibits session allowed attendees to connect with other professionals they might not see on a regular basis. It is this mixture of technical and social interactions that makes this conference unique and keeps attendees coming back year after year.

I would like to thank the entire staff at Beaver Run for making the conference a pleasant experience for the attendees. I also want to recognize Amy Delay and Michelle Barath of Lockheed Martin Space and Lis Garratt of Ball Aerospace for organizing the conference meetings, preparing attendee materials, and ensuring the conference ran smoothly.

Jastesh Sud
Conference Chairperson
2020 AAS Guidance and Control Conference

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Part II

STUDENT INNOVATIONS IN GUIDANCE, NAVIGATION AND CONTROL

Session 1

National Chairpersons:

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David Geller, Utah State University

Local Chairpersons:

Ian Gravseth, Ball Aerospace

Heidi Hallowell, Ball Aerospace

The following paper was not available for publication:

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AAS 20-001 to -010 and AAS 20-019 to 020

AAS 20-011

AUTONOMOUS GUIDANCE FOR ROBUST ACHIEVEMENT OF SCIENCE OBSERVATIONS AROUND SMALL BODIES

Kenshiro Oguri[*] and Jay W. McMahon[†]

To carry out precise scientific observations around small bodies, the spacecraft orbit needs to be controlled within some prescribed accuracy over the observation campaign. At the same time, dynamical environments around small bodies are complex and uncertain, leading to highly perturbed, uncertain orbital dynamics. To ensure desired science outcome under such complexity and uncertainty, this paper presents a stochastic optimal control approach to develop a guidance algorithm that plans robust trajectory correction maneuvers. The solution method is formulated as a convex optimization problem, which yields a sequence of feedback policies that compute probabilistically robust correction maneuvers. The developed approach is numerically demonstrated with a small-body global mapping scenario on a resonant terminator orbit around asteroid Bennu, which offers a wide variety of mapping geometries compared to the classical terminator orbits. [View Full Paper]

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AAS 20-012

ROOT LOCUS ANALYSIS OF THE FROA AND FROA/TDOA GEOLOCATION PROBLEM

Christopher Ertl,[*] Steven Beseler,[†] John Christian[‡] and T. Alan Lovell[§]

Geolocation of an unknown ground-based transmitter that produces Radio Frequency (RF) signals has many practical applications. Using two orbiting receivers, the Frequency-Ratio-of-Arrival (FROA) and Time-Difference-of-Arrival (TDOA) equations can be expressed as sets of polynomials. In this paper we apply a root locus technique to analyze the behavior of the solutions (i.e., polynomial roots) to the system as error is added to the RF measurements. The objective of the root locus approach is to discern receiver orbital geometries leading to solution ambiguities, determine solution sensitivity to uncertainty, and deduce instances where the system provides zero valid solutions. This analysis yields a better understanding of the polynomial system's capabilities and limitations as a solution to the RF-based ground-to-space geolocation problem.

[View Full Paper]

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AAS 20-014

LOW-THRUST EARTH-MOON TRANSFERS VIA MANIFOLDS OF A HALO ORBIT IN THE CIS-LUNAR SPACE

Sandeep K. Singh,* Brian D. Anderson,† Ehsan Taheri‡ and John L. Junkins§

A renewed interest in revisiting the Moon has blown wide open the previously ajar door to research avenues in the field of Earth-Moon transfer trajectories. While the advent of low-thrust propulsion systems has opened up possibilities to undertake more complicated missions, designing optimal transfer trajectories in this domain is no easy feat. Historically, the Circular Restricted Three Body Problem (CR3BP) assumptions have been extensively used for trajectory design in the cis-lunar space. The existence of natural pathways, also known as invariant manifolds, which wind on and off a close vicinity of periodic orbits existing near the libration points, can be leveraged to design more efficient transfer trajectories. In this paper, we study the transfer of a small spacecraft to a low-altitude moon orbit by making use of the manifolds of a chosen L1 Halo orbit. We demonstrate the practicality for a piece-wise, minimum-time transfer that riding the manifold in either direction from the Halo orbit provides, which directly enables more mission objective complexity. [View Full Paper]

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A COMPOSITE FRAMEWORK FOR JOINT OPTIMIZATION OF TRAJECTORY AND PROPULSION SYSTEM DESIGN

Vishala Arya,* Ehsan Taheri† and John L. Junkins‡

Indirect optimization methods convert optimal control problems (OCPs) into two- or multipoint boundary-value problems. A highly desirable feature of indirect methods, specifically for space applications, is that high-resolution trajectories can be generated, which satisfy the first-order necessary conditions of optimality. We utilize the features of a novel Composite Smoothing Control (CSC) framework to formulate and solve the problem of simultaneous trajectory optimization and propulsion subsystem design of spacecraft. A reasonable breakdown of the spacecraft mass is adopted, where the impact of power produced by the solar arrays and its contribution to the total spacecraft mass are considered. The joint optimization problem of spacecraft power subsystem parameters along with the main trajectory is solved to maximize the payload delivered. The proposed framework reduces the original, difficult-to-solve, multi-point boundary-value problem into a two-point boundary-value problem with continuous, differentiable control inputs. Utility of the proposed construct is demonstrated through a low-thrust, multi-revolution, multi-year rendezvous maneuver to asteroid Dionysus with a variable-specific-impulse, variable-thrust engine.

[View Full Paper]

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THE DESIGN OF A SPACE-BASED OBSERVATION AND TRACKING SYSTEM FOR INTERSTELLAR OBJECTS

Ravi teja Nallapu,[*] Yinan Xu,[†] Abraham Marquez,[†] Tristan Schuler[‡] and Jekanthan Thangavelautham[§]

The recent observation of interstellar objects, 1I/ ‘Oumuamua and 2I/ Borisov cross the solar system opened new opportunities for planetary science and planetary defense. As the first confirmed objects originating outside of the solar system, there are myriads of origin questions to explore and discuss, including where they came from, how did they get here and what are they composed of. Besides, there is a need to be cognizant especially if such interstellar objects pass by the Earth of potential dangers of impact. Specifically, in the case of ‘Oumuamua, which was detected after its perihelion, passed by the Earth at around 0.2 AU, with an estimated excess speed of 60 km/s relative to the Earth. Without enough forewarning time, a collision with such high-speed objects can pose a catastrophic danger to all life Earth. Such challenges underscore the importance of detection and exploration systems to study these interstellar visitors. The detection system can include a spacecraft constellation with zenith-pointing telescope spacecraft. After an event is detected, a spacecraft swarm can be deployed from Earth to flyby past the visitor. The flyby can then be designed to perform a proximity operation of interest. This work aims to develop algorithms to design these swarm missions through the IDEAS (Integrated Design Engineering & Automation of Swarms) architecture. Specifically, we develop automated algorithms to design an Earth-based detection constellation and a spacecraft swarm that generated detailed surface maps of the visitor during the rendezvous, along with their heliocentric cruise trajectories. The constellation is designed as an optimal zenith-pointing Walker-Delta constellation that meets a specified detection success rate, despite being subjected to pointing constraints and random spacecraft outages. The heliocentric trajectories of the spacecraft swarm are then designed as optimal Lambert arcs that meet launch and arrival requirements. Finally, the operations of swarm around the visitor are optimized to meet a coverage requirement specified by the mission designer. A crucial challenge faced while studying the spacecraft coverage arises from the tumbling dynamics of the visitor. Additionally, the uncertainty in the spin axis of these objects, and their non-spherical shapes prohibit the use of deterministic coverage modeling algorithms. To address these challenges, we develop a new method to study the spacecraft coverage, called the dual-sphere method, where the irregular body is decomposed into two spheres to compensate for its range and field of view. We then optimize the swarm trajectories that statistically meet the coverage requirement using a Monte-Carlo simulation over the uncertainties. Finally, the algorithms described are demonstrated by designing a notional mission to detect and map 1I/ ‘Oumuamua, assuming there was enough warning time, using the IDEAS architecture. [View Full Paper]

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INVESTIGATION OF PRANDTL-ISHLINSKII HYSTERESIS COMPENSATION FOR DEEP SPACE OPTICAL COMMUNICATIONS POINTING CONTROL*

Lindsey A. Marinello† and John Y. Liu‡

This paper studies the simulated performance of the Deep Space Optical Communication (DSOC) laser downlink pointing control system that has a pointing requirement at the sub-microradian scale. To achieve the required pointing precision, the DSOC Flight Laser Transceiver (FLT) point-ahead mirror (PAM) employs piezoelectric actuators, which are widely used in precision applications due to their high motion resolution, rapid response, and high output forces. However, a piezoelectric actuator's performance is often limited by nonlinearities in their response, most significantly hysteresis. To study the effect of hysteresis on our simulated pointing performance, an invertible hysteresis model is developed using the Classical Prantdl-Ishlinskii (CPI) method. The simulation includes models of DSOC hardware and electronic system components based on key parameters (bias, frequency response, noise), with the hysteresis modeled in the PAM piezo actuator dynamics. A Proportional-Integral controller provides feedback with measurements from two potential sources: strain gauge sensors or a photon-counting camera. To compensate for hysteresis behavior, a feedforward inverse CPI hysteresis model is implemented in the control system. Two CPI models are built using different sampling methods (uniform sampling and cosine spacing) and controller performance is compared. For the maximum command range of ±400 μrad at 1 mHz, results show that the feedforward combined with feedback control reduces output tracking error by 50% or 58% (to 0.20 or 0.38 μrad) compared to feedback control alone (from 0.40 or 0.90 μrad), corresponding to the uniform-sampled and cosine-sampled CPI models, respectively. [View Full Paper]

* The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

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AAS 20-018

MULTIFUNCTIONAL STRUCTURES FOR SPACECRAFT ATTITUDE CONTROL[*]

Vedant,[†] Albert E. Patterson[‡] and James T. Allison[†‡]

A new attitude control system called Multifunctional Structures for Attitude Control (MSAC) is explored in this paper. This system utilizes deployable structures to provide fine pointing and large slewing capabilities for spacecraft. These deployable structures utilize distributed actuation, such as piezoelectric strain actuators, to control flexible structure vibration and motion. A related type of intelligent structure has been introduced recently for precision spacecraft attitude control, called Strain Actuated Solar Arrays (SASA). MSAC extends the capabilities of the SASA concept such that arbitrarily large angle slewing can be achieved at relatively fast rates, thereby providing a means to replace Reaction Wheel Assemblies and Control Moment Gyroscopes. MSAC utilizes actuators bonded to deployable panels, such as solar arrays or other structural appendages, and bends the panels to use inertial coupling for small-amplitude, high-precision attitude control and active damping. In addition to presenting the concept, we introduce the operational principles for MSAC and develop a lumped low-fidelity Hardware-in-the-Loop (HIL) prototype and testbed to explore them. Some preliminary experimental results obtained using this prototype provided valuable insight into the design and performance of this new class of attitude control systems. Based on these results and developed principles, we have developed useful lumped-parameter models to use in further system refinement. [View Full Paper]

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SMALL SAT GUIDANCE,
NAVIGATION AND CONTROL

Session 2

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AAS 20-021

PASSIVE ROLL STABILIZATION OF THE NEAR EARTH ASTEROID SCOUT SOLAR SAIL MISSION

Ivan Rodrigues Bertaska,* Andrew Heaton,† Juan Orphee‡ and Benjamin Diedrich§

The Near Earth Asteroid (NEA) Scout is a small satellite, solar sail mission set to launch on Artemis I. Analysis of the NEA Scout solar radiation pressure model determined that, for certain solar incidence angles, there exists at least one locally stable equilibrium point about the "roll" axis, or the axis normal to the solar sail plane. This analysis is extended to three other geometrically similar solar sail models, and a Lyapunov stability analysis is conducted demonstrating that the stable equilibria are locally stable for the majority of roll angles in a wide range of solar incidence angles. Under certain assumptions, it is possible that only two axis control is required for non-spinning solar sails. If the roll axis is controlled, an active rate damping controller can be designed to asymptotically stabilize the system. Simulation results are presented that follow the stability analysis, where in the homogenous case, the system enters a limit cycle and, in the actively damped case, the system asymptotically converges to the equilibrium point.

[View Full Paper]

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ADVANCING ASTEROID SPACECRAFT GNC TECHNOLOGY USING STUDENT BUILT CUBESAT CENTRIFUGE LABORATORIES

Ravi teja Nallapu,[*] Stephen Schwartz,[†]
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Asteroid science, technology, and exploration is an important and exciting research and education theme at the University of Arizona (UA) that encompasses the College of Science and College of Engineering. Here we outline UA's future efforts in developing new facilities and technologies to advance asteroid exploration with major implications to GNC. UA is planning to develop a research and education center called ASTEROID (Asteroid Science, Technology and Exploration Research Organized by Inclusive eDucation (ASTEROID) funded by NASA. This proposed program envisions project-centric, hands-on education that would place UA students and transfer students from the nearby Pima Community College and the University of Puerto Rico, Humacao in cutting-edge research labs at the UA and in direct collaboration with NASA JPL. UA, Pima, and Univ. of Puerto Rico students would be tasked with developing an exciting series of CubeSat missions. First among these is the development of the AOSAT+ CubeSat mission concept which is presented in this paper. The mission consists of a 12U CubeSat that will operate as a centrifuge laboratory in low Earth orbit. The CubeSat will carry crushed meteorite, along with a suite of science instruments. The spacecraft will rotate at 0.1 to 1.1 RPM to simulate the milli-gravity environment of a desired small body. A major challenge with operating a centrifuge spacecraft is that it contains shifting masses, which result in perturbation torques on the spacecraft. This requires a robust attitude controller to spin the spacecraft at its target rotation speed. This work presents the development of a sliding mode attitude control law that enables the operation of the AOSAT+ Centrifuge mode. [View Full Paper]

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AAS 20-024

DECENTRALIZED SPACECRAFT SWARMS FOR INSPECTION OF LARGE SPACE STRUCTURES

Byong Kwon[*] and Jekan Thangavelautham[†]

The emergence of increasingly sophisticated and modular small satellites is expected to enable in-space assembly of large space observatories, space infrastructure, such as propellant depots and communication relays, and larger modular interplanetary spacecraft. The key is the modular assemble of these space architectures that enables quick assembly of more capable structure and spacecraft with longer range to reach unexplored planetoids, moons, and asteroids in the outer solar system. A key task to assembling small modular structures into a larger structure is the need for careful verification to ensure all the pieces are locked in place. Attempts to minimize or eliminate the use of human astronauts for such tasks would be a major technological achievement and welcome simplification of the overall complexity of the system. In this paper, we present a neural network robotic controller, the Artificial Neural Tissue (ANT), to perform decentralized control of multiple robots for optimal area coverage of large structures. With this robotic controller, there is no supervisor or hierarchy among the robots. In computer simulations, robots can achieve near-optimal parallelism, where increasing the number of robots, *n*, allows the task to be completed in T1/n time, where T1 is the time for one robot to complete the entire task. The robotic controllers are evolved using Darwinian methods in simulation. The fittest controllers can then be tested in high-fidelity simulations or on robotic hardware. To date, our simulation results show the controller enabling multiple robots to self-assign different regions for different robots and thus minimizing covering the same area twice by a single, or multiple robots. The simulations have been extended to various shape primitives including rectangular, square, circular and triangular areas. We find the controllers being able to repeatedly find optimal or near-optimal solutions without requiring human supervision. In fact, some of the solutions could be considered human competitive as they match or exceed human capabilities in solving the problem. Our next steps are to demonstrate the controllers using high-fidelity dynamics simulators, followed by demonstrations on robotic hardware in laboratory. [View Full Paper]

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AAS 20-025

MOBILITY, POWER AND THERMAL CONTROL OF SPHEREX FOR PLANETARY EXPLORATION

Himangshu Kalita* and Jekan Thangavelautham†

Some of the high priority targets outlined in the Planetary Science Decadal survey includes extreme environments of the Moon, Mars and icy moons that includes caves, canyons, pits, cliffs, skylights and craters. Exploration of these extreme and rugged environments remains out of reach from current planetary rovers and landers; however, the 2015 NASA Technology Roadmaps prioritizes the need for next-generation robotic and autonomous systems that can explore these extreme and rugged environments. We had presented an architecture of small, low-cost, modular spherical robot called SphereX that is designed to hop and roll short distances for exploring these extreme environments. The robot uses commercially off-the-shelf components for its electronics and communication. For mobility, the robot uses a H2/O2 propulsion system consisting of one thruster along with a 3-axis reaction wheel system to perform controlled hopping and rolling. For power, the robot uses PEM fuel cells to generate power on demand by utilizing hydrogen and oxygen. To avoid cryogenic storage, hydrogen and oxygen for the propulsion and power system is generated on demand with a water activated lithium hydride (LiH) hydrogen generator and a catalytic decomposition-based lithium perchlorate (LiClO4) oxygen generator. Moreover, for the robot to survive extreme temperature ranges on the target environment, it consists of a thermal control system that relies on both active and passive thermal control elements in the form of a low emissive silver coating, a low conductive silica aerogel insulation layer, a variable emittance coating, a heat switch and an electric heater. In this paper, we present detailed control strategies for mobility, power and thermal system of SphereX for it to survive on a target environment and explore with optimal use of the chemicals. [View Full Paper]

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GNC OF SHAPE MORPHING MICROBOTS FOR PLANETARY EXPLORATION

Jekan Thangavelautham,[*] Rachel Moses,[†] Petra Gee,[†] Tristan Schuler,[‡] Himangshu Kalita[§] and Sergey Shkarayev[**]

In this paper we analyze the feasibility of inflatable microbots that can roll, crawl, hop and hover. Guidance, Navigation and Control is critical to the success of the microbot concept. Each microbot will have a mass of 0.25 kg, a stowed volume of 10 cm × 3 cm × 1 cm and consists of a compact system on a board, comparable to a smartphone. For this size and volume, thousands can be dispersed on a planetary surface. These microbots can operate as swarm, with the advantage of concurrently covering the ground and atmosphere. The small footprint of these platforms could make them ideal secondary or tertiary payload on large rovers and landers. This main board would contain solar photovoltaics for power generation, an onboard computer, IMU, camera, a series motors and actuators, a MEMS powder or gas pump and MEMS vacuum pump. Importantly the robot would contain a set of inflatable bladders. The system would not use a battery due to its inherent vulnerability to temperature. Depending on their application, these bladders would be filled with CO2 or filled with Martian regolith that would be vacuumed thus rigidizing into a solid structure or filled with hydrogen. The hydrogen filled microbots would float and hop over areas of interest. The bladder will be loosing some of the hydrogen over time and hence more hydrogen will be produced on demand to maintain a set average altitude. The ground based microbots by turning soft or rigid on demand, can crawl over obstacles or even sloped surfaces. Surfaces with very few rocky obstacles would benefits from having wheels. Here the wheels would consist of the inflatable bladder filled and rigidized with Martian regolith. When it is flat ground, with few obstacles, options include inflating sphere-shaped bladder with CO2 that can be blown by the Martian wind. [View Full Paper]

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AAS 20-027

A MULTIPLICATIVE EXTENDED KALMAN FILTER FOR LOW EARTH ORBIT ATTITUDE ESTIMATION ABOARD A 0.5U SMALLSAT

Omar F. Awad[*] and Robert H. Bishop[†]

Attitude estimation on small satellites is much more challenging in the absence of precision sensors providing external attitude measurements, such as a star trackers, sun sensors and Earth horizon sensors. Due to the size, power, and mass constraints of small satellites of with volume less than 500 cm^3 employing these precision sensors may not be practical. The proposed solution investigated here is to address the sensor deficit using a multiplicative extended Kalman filter capable of estimating attitude using a radically inexpensive inertial measurement unit, magnetometer, and the global positioning system. The key is that the computational capability of inexpensive central processing units can be utilized to host a high-fidelity magnetic field model that combined with the available measurements can be used to form a quaternion measurement processed by the multiplicative extended Kalman filter to produce a reliable attitude estimate. The results show that attitude estimates under 5 degrees of accuracy may be achievable. [View Full Paper]

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DESIGN AND PERFORMANCE OF AN OPEN-SOURCE STAR TRACKER ALGORITHM ON COMMERCIAL OFF-THE-SHELF CAMERAS AND COMPUTERS

Samuel Pedrotty,* Ronney Lovelace,* John Christian,†
Devin Renshaw‡ and Grace Quintero‡

Recent frustration in finding low size, weight, power (SWaP), cost, and lead time star trackers has driven an internal research and development effort at Johnson Space Center (JSC) in partnership with Rensselaer Polytechnic Institute (RPI) to develop and demonstrate a commercial off-the-shelf (COTS) camera and COTS computer-based star tracker system. A set of open-source algorithms has been developed and their function demonstrated on multiple low-cost COTS single board computers (SBCs) across a variety of operating systems and COTS cameras. The goal of this effort is to release the software and setup guide to the community in order to reduce spacecraft development costs while increasing their capability (perhaps most of interest to low-cost missions like CubeSats). This material will show the high level architecture of the system, detail the algorithm, various tested configurations, and results. Forward work and applications will also be discussed. [View Full Paper]

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ADVANCES IN HARDWARE

Session 3

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Scott Cryan, NASA Johnson Space Center

Local Chairpersons:

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Jim Russell, Lockheed Martin Space Systems Company

Mathew Sandnas, Ball Aerospace

The following paper was not available for publication:

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AAS 20-039 to -040

AAS 20-031

RVS®3000-3D LIDAR – GATEWAY RENDEZVOUS AND LUNAR LANDING

Christoph Schmitt,[*] Sebastian Dochow,[*] Michael Windmüller,[*] Johannes Both[*] and Olivier Mongrard[†]

The return of human presence in cis-lunar space and on the surface of the Moon for missions of increasing durations will be a key milestone towards the ultimate goal of manned missions to Mars. The assembly, operation and supply of the Gateway, representing the necessary human outpost in cis-lunar orbit and a key node in the lunar transportation architecture, will therefore be one of the major key challenges in the upcoming years. For autonomous rendezvous and docking with the Gateway intelligent relative navigation sensors are required. Jena-Optronik's new 3D LIDAR called RVS®3000-3D represents a solution to this challenge via the combination of a high resolution scanning LIDAR with robust pose estimation algorithms. The new generation LIDAR benefits from the legacy of 48 delivered RVS® sensors which all flew flawlessly to the International Space Station on board of ATV, Cygnus and HTV spacecrafts. The RVS®3000-3D LIDAR hardware successfully reached TRL9 via its maiden flight to ISS in 2019 on Cygnus NG-11 and several more units are under contract and even already delivered for the upcoming missions. In the paper we present 6DOF pose estimation performance estimates of the RVS®3000-3D vs. the International Docking Adapter (IDA), which will be used on ISS for the crew commercial program and is also foreseen as the standard docking interface for the Gateway. The simulations are based on experience and data gathered with RVS®3000 Engineering Model in several ground tests, e.g. vs. IDA FM3 at the Kennedy Space Center. In parallel to the establishment of the Gateway station in lunar orbit, a series of robotic mission to the lunar surface are foreseen, paving the way for human return. For autonomous and safe descent high resolution terrain mapping is required to detect and avoid hazards, especially in the more challenging polar regions of interest. For this application the RVS®3000-3D is also an excellent solution since it was designed to address long range and uncooperative targets. In the paper test results obtained with a lunar mockup up to 1000m will be presented outlining the RVS®3000-3D's imaging capabilities vs. lunar regolith. Finally, intelligent algorithm solutions for dense hazard map generation and safe landing spot detection will be presented. [View Full Paper]

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AAS 20-032

THE MAGNETICALLY CLEAN REACTION WHEEL: IS ACTIVE MAGNETIC FIELD COMPENSATION A FEASIBLE SOLUTION?

Anja Nicolai,* Stephan Stoltz,* Lisa Hafemeister,* Olaf Hillenmaier,† Christian Strauch† and Dr. Sebastian Scheiding*

Many scientific satellite mission instruments rely on magnetic field measurements or are influenced by the satellite's magnetic dipole moment. Also, for attitude control, the magnetic dipole moment of the satellite causes disturbance torques when interacting with the Earth's magnetic field. Main contributors to the magnetic field of a satellite are the reaction wheels. Their internal design (electric motors, ferromagnetic parts) and high-speed operation, result in significant electromagnetic stray fields in various frequency ranges. To meet magnetic cleanliness requirements and prevent high magnetic disturbance torques, reaction wheels are often housed in additional shielding on-board the satellite. This results in a significant mass increase and requires more magnetic (shielding) material on-board the satellite.

Previous works have described the on-going efforts in the magnetically clean reaction wheel design. This paper summarizes these efforts and describes the results of the magnetically clean reaction wheel project. Final Test results, reflecting the performance and the magnetic characteristics of the wheel will be presented. Magnetic field mitigation techniques have been implemented in the wheel and the final impact on the magnetic footprint is discussed. The most novel mitigation technique, the active compensation with integrated coils, is analyzed in detail and the feasibility and practicability of the approach is determined. [View Full Paper]

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AAS 20-033

GPS NAVIGATION FROM GEO-TRANSFER TO GEOSYNCHRONOUS ORBIT: A NEW RECEIVER FOR EFFICIENT ELECTRIC ORBIT RAISING

Yu Nakajima,[*] Toru Yamamoto,[†] Ryo Harada,[‡] Satoko Kawakami[§] and Susumu Kumagai[**]

GPS navigation for Geo-Transfer Orbit was developed considering the characteristics of Electrical propulsion Orbit Raising (EOR). It requires longer time to reach GEO by EOR. In addition, the attitude of a satellite must be set specifically for EOR, which may affect the visibility of a GPS receiver. This study de-signed a solution for a satellite to use GPS in a GTO under these constraints with limited number of antennas. The optimum position and direction of the antennas were determined from the results of our analysis. A GPS simulator tested the developed GPS receiver and verified its performance. [View Full Paper]

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AAS 20-034

ASTRO XP – FIRST TEST RESULTS

U. Schmidt,[*] J. Reichardt,[†] P. Petruck,[‡] R. Würl,[§]
S. Fröhlich[**] and I. Steinbach[††]

ASTRO XP is a high accuracy star tracker solution enabling the sub-arc-seconds accuracy range and broadening thereby the successful ASTRO-star tracker product series of Jena-Optronik. The pre-development contract received from the European Space Agency was successfully finished with the integration and the test of a prototype optical head. The very high accuracy of the ASTRO XP star tracker has been achieved due to significant improvements in almost all contributing technology domains like optical systems, digital imaging, processing algorithms, astrophysics, material selection and verification & test approaches. The paper will present and discuss the major challenges, which needed to be solved during the fundamental design process as well as the first promising test results. In addition, the night sky tests provided valuable results showing some interesting lessons learned and potential for further improvements in the algorithmic and data handling. The guide stars used as ultimate angular references have been selected from the GAIA data release 2 astrometric parameter solution, the todays most accurate and complete stellar object data source. [View Full Paper]

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AAS 20-035

PRELIMINARY TEST RESULTS FROM ARIETIS, A HIGH TO MEDIUM PERFORMANCE, HI-REL, SPACE QUALIFIED GYRO

Jose Beitia,* Raouia Oubellil,† Alberto Torasso‡ and Steeve Kowaltschek§

In February 2018, InnaLabs introduced ARIETIS at the 41st Annual AAS Guidance, Navigation and Control Conference [1]. ARIETIS is a Hi-Rel space rate measurement unit, developed with the support of ESA and based on InnaLabs proprietary Coriolis Vibratory Gyroscope (CVG) technology which is currently used in commercial products for land, marine, and space LEO applications. Two years have now passed, and InnaLabs is delighted to witness a significant traction in the marketplace with that product, particularly in Science missions, Navigation, Earth Observation, and Telecom.

ARIETIS is instrumental in InnaLabs strategy for access to Space as it generates several new capabilities in InnaLabs gyroscopes at both electronic and Sensing Element (SE) levels. An enhanced gyro digital control loop system is being implemented featuring novel bias and scale-factor in-loop compensation techniques. Also, the gyroscope SE is made smaller and less sensitive to vibrations and micro-vibrations based on the implementation of an innovative dynamic balancing procedure. Ultimately, the key characteristics of ARIETIS are a low Angular Random Walk parameter (ARW) (i.e. ARW ≤ 0.005 °/√hr), in-run bias of less than 0.1°/hr 1σ, and bias temperature stability of ~ 1°/hr 1σ, delivered in a small, robust and low power consumption package.

After a brief description of the InnaLabs CVG basic principles, this paper provides an update on ARIETIS architecture, including the CVG SE, its key design features and the budget parameters. A comprehensive description of the digital control system being implemented is also provided, with emphasis on the selected parameters for achieving low noise and meeting bias performance requirements. Breadboard test results are presented to support the current progress, both at the CVG sensing element and of the overall digital gyroscope. [View Full Paper]

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AAS 20-036

A LOW-COST RADIATION-HARDENED ASIC FOR CORIOLIS VIBRATORY GYROSCOPE CONTROL

Peter W. Bond,* Jeremy D. Popp† and Anthony D. Challoner‡

Reducing size, weight, and cost of Guidance, Navigation, and Control and precision space pointing has been a significant issue for small satellites and even larger spacecraft. Accessibility to radiation-hardened electronics for gyroscope control systems is also a concern. In addition, the newer class MEMS Coriolis Vibratory Gyroscopes (CVG's) are highly influenced by very minor changes in assembly, packaging, and integration to their operating circuits.

A dedicated Radiation-Hardened Application Specific Integrated Circuit (ASIC) is being developed by Inertialwave under a NASA Phase II SBIR to provide chip-size gyro controls that have the potential to significantly reduce cost and size of future IMU's while possibly improving performance, especially for small satellite and CubeSat attitude determination, guidance control, and space precision pointing systems.

Inertialwave has already developed gyro control ASICs for terrestrial applications, is currently in the process of testing these with several Coriolis Vibratory Resonators and is demonstrating navigation-grade gyroscope performance. Recent testing has validated the front-end electronics Total Ionizing Dose (TID) survivability, and future testing is planned for a new radiation-hardened version of the full digital control ASIC. Planned work includes Heavy Ion Cyclotron testing for single events as well as TID testing.

Based on testing performed to date and the planned work, we expect to have demonstrated IMU performance using the current terrestrial ASICs in January 2020, and fully functional radiation-hardened control ASICs in late 2020. [View Full Paper]

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AAS 20-037

AURIGA STAR TRACKER FLIGHT HERITAGE ON INAUGURAL AIRBUS ONEWEB SATELLITES CONSTELLATION

**Damien Piot, Benoit Gelin, Marc Maksimous*
Audrey Lieutaud and Bruno Vignon†**

On 27 February 2019, twelve Auriga CMOS star trackers were successfully launched aboard the inaugural set of six satellites for the Airbus OneWeb Satellites constellation. This paper presents the first results of this new and revolutionary star tracker that was designed specifically for the small satellite constellation market. With its low mass, small size, high performance, & robust attitude determination, Auriga star tracker can be produced in large volumes with an incredibly short lead-time. Data collected during the first months of the in-orbit validation phase was thoroughly analyzed and compared to predicted performance from simulations and ground tests. Attitude accuracy, straylight levels and Sun exclusion angle, operation with Moon in the field of view and star catalog have all been verified. Auriga is now available in multiple form factors to address other applications requiring large or small quantities. [View Full Paper]

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HUMAN SPACEFLIGHT/
DEEP SPACE GATEWAY

Session 4

National Chairpersons:

Tim Straube, NASA Johnson Space Center

Howard Hu, NASA Johnson Space Center

Diane Davis, NASA Johnson Space Center

Local Chairperson:

Harvey Mamich, Lockheed Martin Space Systems Company

The following paper numbers were not assigned:

AAS 20-049 to -050

AAS 20-041

ANALYSIS OF CISLUNAR AUTONOMOUS NAVIGATION WITH STARNAV AND OPNAV

Paul McKee,* John A. Christian† and Christopher D'Souza‡

Both Orion and Gateway have requirements for autonomous navigation to ensure crew safety if communication with Earth is lost. Existing designs address this problem using exclusively optical navigation (OPNAV) observations of the Moon and, in some instances, the Earth. These OPNAV algorithms make use of the observed location of the body's lit limb or surface features (landmarks) in digital imagery. Purely OPNAV-based navigation solutions, however, suffer from relatively poor estimates of velocity. This deficiency may be addressed by the recently proposed StarNAV technique, which directly estimates velocity by measuring the perturbation in apparent star direction due to stellar aberration. This work provides the first-ever analysis quantifying the improvement that StarNAV observables may offer for the autonomous navigation of crewed systems in cislunar space. [View Full Paper]

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AAS 20-042

EVALUATING RELATIVE NAVIGATION FILTER DESIGNS AND ARCHITECTURES FOR HUMAN SPACEFLIGHT

David Woffinden*

For human spaceflight and exploration, relative navigation plays a pivotal role especially when missions require precision landing or on-orbit rendezvous, proximity operations, and docking. Objectively evaluating the various relative navigation filter architectures and designs for multiple flight phases, in multiple domains, utilizing multiple sensors in multiple configurations may initially appear overwhelming and impractical. This paper outlines techniques to systematically analyze and compare the performance of an arbitrary number of filter designs in a variety of different architectures where several navigation filters may run simultaneously. This general formulation is then applied to demonstrate the evaluation of different relative navigation filter formulations and architectures for a precision lunar landing scenario with reference to its application to rendezvous, proximity operations, and docking in cis-lunar space. A summary is provided to highlight the strengths and limitations to potential relative navigation system designs intended to support human spaceflight. [View Full Paper]

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AAS 20-043

PATH-ADAPTIVE GUIDANCE ALGORITHM TRADES FOR A TWO-STAGE LUNAR DESCENT VEHICLE

Jason M. Everett* and Anand R. Iyer*

For the next generation of NASA's missions, explicit, path-adaptive descent guidance algorithms must provide the stability and customizability required for a safe and efficient descent to the lunar surface, while also meeting program and vehicle constraints. Several descent algorithms have been flown and tested for single-stage landers through the Apollo and Altair programs, but thus far little analysis has been conducted involving the application of these algorithms to a two-stage descent vehicle. Due to payload mass and volume constraints of the existing fleet of launch vehicles, multi-stage descent architectures are a unique option for achieving the greatest possible mass to lunar surface. This paper seeks to compare the performance of guidance configurations of a lunar lander system consisting of two stages, one of which separates partway through descent. Through development of this paper, an optimization suite has been written that is specifically designed for optimizing planetary non-atmospheric two-stage descent trajectories, and is used as a baseline to compare the guidance algorithms tested. Time-to-go computational methods and ignition logic routines that may be employed in a lunar environment are also discussed. Preliminary results are presented that show relative performance metrics for a range of different guidance algorithm configurations. [View Full Paper]

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AAS 20-044

POWERED DESCENT GUIDANCE FOR A CREWED LUNAR LANDING MISSION

Sergio A. Sandoval* **and Ping Lu†**

NASA's Artemis Program aims at returning astronauts to the lunar surface as early as 2024. This paper applies a recently developed guidance method dubbed fractional-polynomial powered descent guidance (FP^2DG) to a crewed mission landing at the South Pole of the Moon. The FP^2DG method inherits the maturity and flight-proven legacy of the Apollo lunar descent guidance law, yet, offers much greater flexibility in trajectory shaping and performance trade. For autonomous operation in a diverse range of situations, the FP^2DG law is aided by an on-board powered descent initiation algorithm to adaptively determine a best timing for engine ignition based on the actual state of the flight. This guidance approach is reviewed first in this paper, then demonstrated in deterministic and Monte Carlo simulations in the lunar landing mission. The guidance approach is shown to be highly robust, accurate, and propellant efficient. [View Full Paper]

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AAS 20-045

GN&C SEQUENCING FOR ORION RENDEZVOUS, PROXIMITY OPERATIONS, AND DOCKING

Peter Z. Schulte,* Peter T. Spehar,† and David C. Woffinden†

As part of the Artemis program to return humans to the lunar surface, the National Aeronautics and Space Administration is planning to use the Orion Multi-Purpose Crew Vehicle to transport crew to a small orbital platform called Gate-way in cislunar space. To facilitate this activity, Orion is required to perform Rendezvous, Proximity Operations, and Docking (RPOD) with both the Gateway and the launch vehicle upper stage.

The Orion spacecraft uses sequencing in the form of Phases, Segments, Activities, and Modes (PSAM) to configure Guidance, Navigation, & Control (GN&C) software during each portion of the mission. Significant updates to Orion PSAM definitions are required for RPOD. This paper describes the process of defining these new sequencing elements, implementing them in prototype flight software, and testing them in an integrated simulation environment.

First, requirements are specified to determine the nominal and off-nominal sequencing behavior necessary to complete the mission. These requirements also specify which software functions should be fully autonomous and which functions require manual interactions from crew or ground operators. Next, the RPOD concept of operations is defined with detailed events listed in a mission timeline. Third, a state machine diagram is developed to show all PSAM states, including all possible transitions between them. After this, the PSAM states and transitions are entered into a sequencing software emulator and parameter values and modes are defined for GN&C software elements. Finally, the PSAM architecture is tested within an integrated simulation environment by connecting it with prototypes of relevant GN&C flight software elements and with detailed vehicle models. After the sequencing design has been finalized and tested, it is implemented in flight software. [View Full Paper]

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AAS 20-046

ATTITUDE CONTROL AND PERTURBATION ANALYSIS OF A CREWED SPACECRAFT WITH A LUNAR LANDER IN NEAR RECTILINEAR HALO ORBIT

Clark P. Newman,* Jacob R. Hollister,* Frederick S. Miguel,* Diane C. Davis† and Daniel J. Sweeney‡

NASA's Gateway Program plans a crew-tended spacecraft in cislunar space to support missions beyond Earth orbit, including crewed lunar lander missions. Vehicles in cislunar space must maintain orbit and phase against perturbations, including venting, unbalanced slew and desaturation maneuvers, attitude errors, and solar pressure mismodeling. This paper investigates the relative attitude control and orbit maintenance costs for a variety of scenarios. First, the costs for a baseline 15-year lifetime scenario are computed. Various perturbations are isolated and varied to assess operational control limitations and fuel costs. Finally, the impacts of missed orbit maintenance maneuvers are assessed under different mission scenarios. [View Full Paper]

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AAS 20-047

PHASE CONTROL AND ECLIPSE AVOIDANCE IN NEAR RECTILINEAR HALO ORBITS

Diane C. Davis,[*] Fouad S. Khoury,[†] Kathleen C. Howell,[‡] and Daniel J. Sweeney[§]

The baseline trajectory proposed for the Gateway is a southern Earth-Moon L_2 Near Rectilinear Halo Orbit (NRHO). Designed to avoid eclipses, the NRHO exhibits a resonance with the lunar synodic period. The current investigation details the eclipse behavior in the baseline NRHO. Then, phase control is added to the orbit maintenance algorithm to regulate perilune passage time and maintain the eclipse-free characteristics of the Gateway reference orbit. A targeting strategy is designed to periodically target back to the long-horizon virtual reference if the orbit diverges over time in the presence of additional perturbations. [View Full Paper]

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AAS 20-048

A PRACTICAL METHOD FOR TRUNCATING SPHERICAL HARMONIC GRAVITY FIELDS, APPLICATION AT THE MOON

Sean McArdle,[*] Ryan P. Russell[†] and Srinivas Bettadpur[‡]

Spherical harmonic gravity fields are among the most common perturbation models for spacecraft applications. Accurate, high-fidelity models exist for Earth, Mars, and the Moon, and their spherical harmonics representations are often truncated for practical use in an ad-hoc fashion. Here, analytic formulas are derived for errors associated with the inclusion and omission of gravity field terms. These commission and omission formulas, respectively, are derived by spatially averaging the expected linearized error in acceleration due to nonspherical gravity, and are a function of spherical harmonic degree, altitude from the nonspherical body, and an additional expected acceleration noise floor. Approximate confidence bounds for the commission and omission errors are compared to determine an appropriate truncation degree. The analytic commission and omission error expressions are numerically verified using a Monte Carlo simulation of a lunar gravity field. Curve-fit coefficients for the lunar gravity field are provided for potential use in lunar mission design, analysis, and flight applications. [View Full Paper]

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PIONEERS/
TECHNOLOGY EVOLUTION

Session 5

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Tooraj Kia, NASA Jet Propulsion Laboratory

Local Chairpersons:

Lee Barker, Lockheed Martin Space Systems Company

Larry Germann, Left Hand Design Corp

The following paper numbers were not assigned:

AAS 20-056 to -060

AAS 20-051

DR. RICHARD BATTIN: INVENTING AND APPLYING MODERN SPACE GUIDANCE WHILE ALSO BEING A MORAL COMPASS

Philip D. Hattis*

All but two years of Richard “Dick” Battin’s career were spent at the MIT Instrumentation Laboratory (IL), its successor The Charles Stark Draper Laboratory, Inc, and teaching MIT graduate students. He intuited solutions to complex dynamics problems, then applied new techniques to address their computational challenges. His focus was development of precision missile and spacecraft guidance. Late 1950s work by Dr. Battin, Dr. J. Halcombe Laning, and Milton Trageser on the design of a spacecraft capable of a round trip Earth-to-Mars mission became the basis for the IL’s 1961 selection to develop the Apollo Guidance, Navigation, and Control (GN&C) system. Battin then led development of the Apollo Guidance Computer (AGC) software. The extraordinary AGC software challenges included fitting all Apollo GN&C functionality within the 38K 16-bit word memory while enabling real-time execution despite a 12 micro-second cycle time. The AGC software met all objectives for all Apollo missions. Battin’s leadership, insights, and collaboration with a brilliant supporting staff enabled this success. He was also a person of strong personal convictions, serving as a moral compass for many. He profoundly believed in and practiced participatory democracy, and led a foundation to facilitate adoption of special needs children. [View Full Paper]

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AAS 20-052

CODENAME CORONA: AMERICA'S FIRST IMAGING RECONNAISSANCE SATELLITE

Cornelius J. Dennehy*

Twenty-five years ago this month, in February 1995, the public learned of the existence of America's first imaging reconnaissance satellite, code-named CORONA. During a series of 145 launches, CORONA satellites photographed vast portions of the Earth's surface. That photography allowed the United States and its allies to track military targets and operations in denied areas and better understand Sino-Soviet strategic military capabilities. The CORONA imagery allowed the U.S. government to make more informed national security decisions, based on accurate information rather than guesswork. Described publicly by many as a scientific test program, the Discoverer Program became highly classified and was given the top secret code name CORONA. The CORONA satellite was placed into orbit by a Thor/Agena launch vehicle. Carried inside an Agena spacecraft, a camera enclosed in a capsule took photographs as it passed through Soviet airspace. The launch of Discoverer I occurred on February 28, 1959. Discoverer II, launched in April 1959, was the first satellite to be stabilized in orbit in all three axes, receive maneuvering commands from Earth, successfully separate its reentry vehicle on command, and de-orbit that vehicle back to Earth. The first successful mid-air capture occurred after the launch and return of Discoverer XIV in August 1960. Although the Discoverer Program officially ended with the launch of Discoverer 38 in February 1962, the secret CORONA Program continued to operate until May 1972, completing 145 missions. This paper will describe the origins of the CORONA Program, as well as some key individuals and companies who engineered and managed this revolutionary satellite system. It will also focus on the technical highlights and accomplishments of the CORONA satellite system. [View Full Paper]

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AAS 20-053

A CAUTIONARY TALE OF A SECRET, A SMALL TEAM, AN ACCELERATED SCHEDULE, AND THE GEMINI IV STATION-KEEPING FAILURE

John L. Goodman*

During the Gemini IV mission in 1965, the first attempt by a NASA human-piloted spacecraft to control relative motion, a station-keeping attempt, ended in failure. Authors have limited their discussions of the failure to the supposed "discovery" by NASA that spacecraft relative motion cannot be controlled the same way that an aircraft is flown. In fact, this was well known to NASA and contractor personnel planning Gemini rendezvous missions. But the real issue was not the supposed "discovery" by NASA that controlling relative motion is counter intuitive. The questions that should have been asked are why was the advanced state of knowledge of relative motion resident in Project Gemini not applied to Gemini IV mission planning and crew training? And why was an unverified procedure presented to the Gemini IV crew? This paper examines the Gemini IV incident from a rendezvous and proximity operations perspective and investigates both the technical and organizational causes of the station-keeping failure. [View Full Paper]

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AAS 20-054

WILLIAM LEAR'S PIONEERING CONTRIBUTIONS TO SPACECRAFT NAVIGATION FILTERING

J. Russell Carpenter,[*] T. James Blucker,[†] John L. Goodman,[‡] James S. McCabe[§] and Thomas D. Bruchmiller[**]

Dr. William M. Lear was one of many unsung heroes of the Apollo Program. His application of the extended Kalman filter, among the first operationally used for ground-based orbit determination, was instrumental in allowing Apollo 11 to land on the Moon. Later he worked for many years at the NASA Johnson Space Center in support of the Space Shuttle Program. Lear developed the Kalman filters that were used for ground monitoring of the shuttle's ascent and entry, and made many indirect contributions to the design of the onboard navigation filters. Lear's "Nyström-Lear" integrator will fly on the NASA Orion spacecraft as part of the onboard software Encke-Beta trajectory predictor. Bill Lear was known by colleagues as a prodigious worker and generous friend, mentoring several generations of navigators through the years. He wrote many technically detailed internal notes and memoranda that continue to serve as an encyclopedia of topics relevant to Kalman filtering and orbit determination for the NASA navigation community.

[View Full Paper]

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AAS 20-055

VOYAGER AND ITS TEAM—A JOURNEY TO THE OUTER PLANETS AND BEYOND*

Aron A. Wolf†

The Voyager Program and the twin Voyager 1 and Voyager 2 spacecraft are legendary, and the mission they continue to fly achieved significant milestones in the history of solar system exploration. NASA launched the two spacecraft in separate months in the summer of 1977. Eventually, between them, Voyager 1 and 2 would explore all four giant outer planets of our solar system, 48 of their moons, and their unique systems of rings and magnetic fields. To achieve this great success, the Voyager team had to work through a series of anomalies, starting with safe mode entries shortly after launch and telecommunications issues in early operations. The Voyager team pioneered deep-space exploration as they learned to solve these and many other problems in the mission's 40-plus years. [View Full Paper]

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ADVANCES IN PROPULSION

Session 6

National Chairpersons:

Jeff Sheehy, NASA Space Technology Mission Directorate

Marc Young, Air Force Research Laboratory

Local Chairpersons:

John Abrams, Analytical Mechanics Associates Inc.

Nick Patzer, Laboratory for Atmospheric and Space Physics

The following papers were not available for publication:

AAS 20-064 (Paper Withdrawn)

AAS 20-067 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 20-069 to -070

PROSPECTS AND CHALLENGES FOR MAGNETIC PROPELLANT POSITIONING IN LOW-GRAVITY

Álvaro Romero-Calvo,* Filippo Maggi† and Hanspeter Schaub‡

The sloshing of liquids in low-gravity entails several technical challenges for spacecraft designers and operators. Those include the generation of significant attitude disturbances, the uncontrolled displacement of the center of mass of the vehicle or the production of gas bubbles, among others. Magnetic fields can be used to control the position of a magnetically susceptible propellant and transform a highly stochastic fluid system (non-linear sloshing) into a deterministic problem (linear sloshing). The employment of magnetic settling forces also produces an increase of the natural sloshing frequencies and damping ratios of the liquid. Despite being proposed in the early 1960s, this approach remains largely unexplored. A recently developed magnetic sloshing control model is here presented and extended, and potential space applications are explored. Technical challenges associated with the reachability, scaling and stability of paramagnetic and ferromagnetic systems are discussed, unveiling a roadmap for the implementation of this technology.

[View Full Paper]

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FLIGHT PERFORMANCE OF THE PROPULSION SUBSYSTEM ON THE GREEN PROPELLANT INFUSION MISSION

Christopher McLean,[*] Brian Marotta[†] and Brad Porter[‡]

Ball Aerospace is flying an AF-M315E green propellant a propulsion subsystem technology demonstration mission using the BCP-100 SmallSat bus as the flight platform. The NASA Space Technology Mission Directorate's (STMD) Green Propellant Infusion Mission (GPIM) is on-orbit, validating performance of an AFM315E monopropellant propulsion subsystem against imposed NASA Level 1 Program Requirements (PLRAs). The propulsion subsystem includes five protoflight 1 N thrusters, four for attitude control and a fifth facilitating higher overall thrust during delta-V maneuvers.

Program requirements include on-orbit characterization of the spacecraft's propulsion capabilities, including 3-axis control, pointing accuracy evaluation, and momentum dumping, all employing the attitude control thrusters. On-orbit measurement of 1 N thruster impulse-bit is performed to characterize thruster health over the course of mission. The attitude control thrusters are canted to maximize the moment-arm between the thrust vector and the CG of the spacecraft, increasing resolution of thrust measurement. Perigee lowering operations of the GPIM spacecraft are performed during delta-V operations. Delta-V operations are accomplished by pulse width modulating the four 1 N attitude control thrusters to provide thrust vector control of the spacecraft while the center 1 N thruster is continuously firing.

The GPIM spacecraft was launched in June of 2019 as a secondary payload on the Air Force's STP-2 Falcon Heavy launch vehicle. This paper summarizes the demonstrated performance of the propulsion subsystem against the Program Level 1 requirements. [View Full Paper]

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AAS 20-063

PERFORMANCE OF THE HYDROS WATER-ELECTROLYSIS THRUSTER*

M. C. Freedman,† M. J. Bodnar,† R. D. Grist,† A. K. Porter† and R. P. Hoyt‡

The HYDROS propulsion system architecture is a pulsed thrust propulsion system with high thrust-to-power and flexible total system performance. The HYDROS system electrolyzes water into hydrogen and oxygen gases, which are stored until a thrust event is commanded. Water is non-toxic, not explosive, and the system is not pressurized on launch, making a HYDROS system the ideal propulsion system for secondary payloads. The HYDROS systems can be operated in two modes: high specific impulse (Isp) (300 s) hotfire thrust event or small impulse bit cold gas thrust events. Two sizes of the HYDROS system have been flight qualified to-date: HYDROS-M for microsatellites and HYDROSC for cubesats. Three HYDROS-M flight units have been delivered to commercial customers. The HYDROS-C unit has been delivered and is currently undergoing spacecraft integration as the first payload for the NASA Pathfinder Technology Demonstrator program, scheduled for launch in 2020. The performance characteristics of both of these as-built systems are outlined in this paper, as well as the scaling flexibility and performance trade space of the system architecture for future missions. [View Full Paper]

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AAS 20-065

MISSION ANALYSIS FOR MARS OPPOSITION MISSIONS 2033 TO 2048

Brian J. Guzek,* James F. Horton† and C. Russell Joyner II‡

NASA and industry are studying future human exploration missions to Mars that occur across multiple mission opportunities between 2030 through 2050. Aerojet Rocketdyne is supplementing previous work with Conjunction Class round-trip Mars missions by studying Opposition Class missions. Opposition Class missions have the advantage of shorter total mission time at the expense of higher delta-V requirements and shorter Mars surface stay time. To achieve this shorter trip time, a Venus gravity assist is utilized to allow either a fast return or a fast outbound transfer. This approach to Mars mission planning is used to inform trades for spacecraft based around chemical, nuclear-thermal, and solar-electric / chemical hybrid propulsion.

NASA Copernicus trajectory software is used to perform the bulk of the trajectory analysis. A patched conics approach with ballistic trajectory is used to construct each mission plan. A Lambert's boundary value problem solver is used for fast calculation, at the expense of a small amount of accuracy. The vis-viva equation is used to adjust the delta-V requirements into the planetary sphere-of-influence. Several reference missions are constructed for each mission opportunity window, and a sweep of mission departure times is run to give insight into delta-V sensitivity and launch period duration.

This paper will discuss the results of preparing this mission data in order to provide the needed information for analyzing the impact of propulsion system performance on Earth-Mars Opposition-Class missions in the 2030-2050 timeframe. Additionally, it will discuss the current state of Aerojet Rocketdyne efforts into developing propulsion solutions for Martian, Lunar, and other deep-space missions. [View Full Paper]

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AAS 20-066

GATEWAY LOGISTICS SERVICES USING HIGH TRL ADVANCED PROPULSION AND FLIGHT PROVEN ISS CARGO ELEMENTS

James F. Horton,[*] Christopher B. Reynolds,[†] Rodney Noble,[‡] William F. Sack,[§] Timothy Kokan[**] and Dennis Morris[††]

NASA's accelerated Artemis program goal of landing astronauts on the moon within the next five years, by 2024, and establishing a sustained presence on and around the Moon by 2028 will require routine delivery of science and consumables at the Gateway lunar orbital outpost which will sit in a lunar near rectilinear halo orbit (NRHO). Due to that schedule compression, reuse of flight-proven cargo elements from the International Space Station (ISS) program can be beneficially leveraged for this cis-lunar application when combined with recent engine developments in chemical and solar electric propulsion (SEP). This approach reduces the investment, development time, and risk management needed with a clean sheet design and provides an avenue for international collaboration in humanity's next step in space exploration.

This paper investigates reusing elements of the Japan Aerospace Exploration Agency (JAXA) / Mitsubishi Heavy Industries (MHI) autonomous H-II Transfer Vehicle (HTV), used for ISS cargo resupply, to deliver 3,400 kg of pressurized cargo and 1,000 kg of unpressurized cargo to the Gateway in a 9:2 lunar synodic L_2 south NRHO. However, to perform the necessary impulse to go beyond low earth orbit (LEO) the original HTV propulsion module has been replaced with advanced Aerojet Rocketdyne propulsion (along with the necessary structure, power, and propellant storage subsystems). Three propulsion module configurations have been analyzed. The first is a xenon-fueled SEP module leveraging NASA's investment in the 13 kW hall thruster and PPU system, known as the Advanced Electric Propulsion System (AEPS), which is being developed for the Gateway's Power and Propulsion element (PPE). The second is a cryogenic module leveraging the next generation LOX/LH2 RL10C-5-1 in development for the NGIS OmegA launch vehicle. The third uses a high-performance pump-fed storable chemical engine known as the XLR-132 (RS-47) that was tested extensively in the 1980's and delivered over 340 seconds of specific impulse (I_{SP}).

Launch vehicle and insertion orbit trades are presented along with trajectory analysis and conceptual designs. The designs are sized to the correct propellant loads and used to fit-check against launch vehicle fairing envelope constraints. MHI's next generation HTV-X design has been evaluated as well for feasibility and is presented as an alternative to the original HTV-based design.

[View Full Paper]

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AAS 20-068

PROSPECTS FOR INTERSTELLAR PROPULSION

Ronald J. Litchford[*] and Jeffrey A. Sheehy[†]

In recognition of the increasing prospects for Earth-like exoplanet discoveries and its significance for spurring future interstellar voyages of discovery, the United States Congress recently directed NASA to undertake an interstellar mission technology assessment report.[‡] In response to this legislative charge to action, NASA has undertaken a series of extramural interstellar workshops aimed at identifying and evaluating technology concepts for enabling an interstellar scientific probe mission, associated technical challenges, technology readiness level assessments, risks, potential near-term milestones, and funding requirements. This paper summarizes these activities and discusses the scientific and technical rationale for a long-term program consisting of incremental, staged technical developments that are extensible for interstellar travel to a nearby star system over many decades. [View Full Paper]

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[‡] House Report 114-605, accompanying H.R. 5393, the FY 2017 Commerce, Justice, Science, and Related Agencies appropriations bill.

HYPERSONICS, RE-ENTRY VEHICLES AND EDL

Session 7

National Chairpersons:

Sam Thurman, Jet Propulsion Laboratory

Henry Cordova, NASA Johnson Space Center

Local Chairpersons:

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DeAnn Redlin Sanders, Ball Aerospace

Ernie Lagimoniere, Sierra Nevada Corp

The following paper numbers were not assigned:

AAS 20-079 to -080

AAS 20-071

SAMPLE-BASED ROBUST UNCERTAINTY PROPAGATION FOR ENTRY VEHICLES

Remy Derollez* **and Zachary Manchester***

This paper introduces a new approach for uncertainty quantification and propagation applicable to entry vehicle trajectories, suitable for use in trajectory optimization and computation of approximate invariant funnels. Because of the lack of precise knowledge of the atmospheres of other solar system bodies, traditional entry trajectory design methods rely on extensive Monte Carlo simulations, leading to accurate results but at high labor and computational costs. Other conventional methods can be faster but require assumptions on the probability distributions of dispersion parameters. The approach developed in this paper represents uncertainties in the system using conservative ellipsoidal bounds. A sample-based strategy inspired by the Unscented Kalman Filter is used to propagate the dynamics and uncertainties around the nominal trajectory. The method is demonstrated on the Duffing oscillator and then applied to a Mars entry vehicle problem using both three-degree-of-freedom and six-degree-of-freedom dynamical models. Its performance is compared with traditional uncertainty quantification methods. [View Full Paper]

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AAS 20-072

ENTRY, DESCENT AND LANDING TRAJECTORY DESIGN METHODS FOR *DREAM CHASER*® SPACEPLANE*

Mark S. K. Muktoyuk,† Remus C. Avram,† Jason M. Tardy,† and Ernest E. Lagimoniere, Jr.‡

Sierra Nevada Corporation's (SNC) Dream Chaser is a reusable lifting body spacecraft designed to transport cargo to and from low earth orbit, reenter the atmosphere in a benign, low-g environment, and land horizontally on a conventional runway. The entry, descent, and landing (EDL) flight regime for this vehicle consists of three standard phases: entry, terminal area energy management (TAEM), and approach & landing (A&L). The entry phase uses a modified version of shuttle bank angle guidance in which a reference drag acceleration profile is tracked via a linear feedback law, with bank reversals to maintain heading. The TAEM phase manages the low altitude energy profile, acquires the desired runway heading, and is designed to navigate a constrained design space with limitations on angle of attack and dynamic pressure while ensuring stringent handover conditions to A&L. This final phase is designed to meet landing performance requirements while enforcing smooth transitions between various piecewise-continuous trajectory segments. This paper presents an overview of the EDL trajectory design process, including a description of methodologies and custom design tools, and presents nominal profiles and Monte Carlo results which demonstrate robustness to plant and navigation dispersions.

[View Full Paper]

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AAS 20-073

ROBUSTIFYING MARS DESCENT GUIDANCE THROUGH NEURAL NETWORKS

Davide Amato,* Shayna Hume,† Benjamin Grace† and Jay McMahon‡

We propose to enhance the robustness of Mars EDL guidance by leveraging knowledge that can be easily gathered from on-board sensors during the descent. This is accomplished by using neural networks to perform online updates of the on-board atmospheric model characteristics. We train a Long Short-Term Memory (LSTM) recurrent neural network to map sequences of measured accelerations into piecewise exponential density profiles that are derived from the Mars GRAM 2010 atmospheric model. The acceleration data is obtained by running closed-loop Mars EDL simulations with the FNPEG numerical predictor-corrector algorithm defining a bank-angle only control law during the entry phase. The trained network achieves a 0.02% root-mean-square error in the prediction of the density training dataset for a small number of samples.

[View Full Paper]

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COMPARATIVE STUDY OF LIFT- AND DRAG-MODULATION CONTROL STRATEGIES FOR AEROCAPTURE

C. R. Heidrich,* E. Roelke,* S. W. Albert* and R. D. Braun†

Aerocapture is frequently identified as an enabling or enhancing technology for exploration of the solar system. During atmospheric flight, the capability of an on-board guidance and control system to actively correct for off-nominal flight conditions is paramount to the success of an aerocapture maneuver. Aeroassist guidance algorithms have historically focused on lift-modulation, where the vehicle adjusts its bank angle or angle of attack as a form of lift steering to achieve precise exit conditions. More recently, alternative control strategies have emerged which use drag-modulation for flight control by changing the ballistic coefficient of the vehicle. While both strategies show promise for improving orbital accuracy in aerocapture, there is only limited understanding of the regions of applicability for these methods. In this paper, a comparative methodology for lift- and drag-modulation control strategies is developed. Representative mission applications at Mars, Titan, and Neptune are taken from the literature for application and comparison. Performance parameters are defined and entry corridor trades are computed across various design parameters. A numerical predictor-corrector guidance strategy is applied using both control methods in order to assess performance under dispersed flight conditions. This research will support aerocapture mission feasibility and assessment by providing designers with a comparison of lift and drag control strategies. [View Full Paper]

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AAS 20-075

TRAJECTORY RECONSTRUCTION FOR THE HTV SMALL RE-ENTRY CAPSULE

Ryo Nakamura,[*] Misuzu Haruki,[*] Shuichi Matsumoto,[*] Satoshi Kobayashi,[†] Issei Kawashima,[†] Kotaro Aoki[‡] and Nobuaki Kikuchi[‡]

The mission of the HTV Small Re-entry Capsule (HSRC) was to demonstrate technologies for retrieving experimental samples from the International Space Station (ISS). One of the key technologies to be demonstrated was a guided reentry technology. To meet a requirement on the landing accuracy better than 10km with under a maximum acceleration of 4G, bank angle modulation based on a range error estimated by real-time integration was used for the guidance. The HSRC was ejected from its mother ship, the H2A Transfer Vehicle (HTV), flown successfully with a newly developed guidance, navigation and control system, and splashed down in the Pacific Ocean near Minamitorishima. This paper presents an overview of the flight results and a reconstruction of the HSRC trajectory. [View Full Paper]

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AAS 20-076

PRELIMINARY DESIGN, TESTING, AND PERFORMANCE OF THE LOFTID NAVIGATION SYSTEM

Joel Amert,* Kyle Miller† and Evan Anzalone‡

The Low Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) involves the first orbital test of an inflatable decelerator. This test involves the LOFTID re-entry vehicle using an inflatable decelerator to re-enter the atmosphere after flying to orbit as a secondary payload. Due to system constraints, including spin stabilization, unknown time of day, a limited space available for antennas, and a heat shield which blocks magnetic fields, the navigation system includes only an inertial measurement unit and a single GPS receiver. As the vehicle is turned off for the first part of the mission and will not receive commands or data from the ground, the navigation system will not have accurate initialization, and will in-stead rely on pre-flight estimates or first measurement estimation. This could result in significant unknown error in the initial state, resulting in needing to initialize the state on-orbit and requires using the single GPS antenna for attitude updates. These design considerations led to using an Extended Kalman filter, modified to perform with these design constraints. A streamlined testing approach, including tests with flight-like rotations, is being used to limit the time and resources needed to test the navigation system while still fully testing the performance and robustness of the navigation system. This testing approach follows the NASA test-as-you-fly principle and allows for early detection of errors and changes that are needed in the software. This results in a navigation system that, even within the design constraints of the mission architecture, will provide the performance and robustness needed of the mission.

[View Full Paper]

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AAS 20-077

DREAM CHASER® SPACEPLANE ENTRY, DESCENT AND LANDING (EDL) GUIDANCE, NAVIGATION AND CONTROL DESIGN (GN&C) OVERVIEW*

Ernest E. Lagimoniere Jr.,† Mathew P. Lyons,‡ Terry L. Carl Jr.,‡ Aaron H. Rainier,‡ Keith D. Speckman,§ Stephen W. Thrasher and Louis S. Breger††**

Dream Chaser is a reusable lifting body space vehicle being designed and built by Sierra Nevada Corporation (SNC) that provides an autonomous low-g reentry capability, returning cargo from low-Earth orbit (LEO) to a horizontal runway landing in support of NASA's Commercial Resupply Service 2 (CRS-2) program. In this paper the design of the Dream Chaser entry, descent and landing (EDL) guidance, navigation and control (GN&C) system will be reviewed with focus on the discussion of novel features, methods and components as well as indication of where robust heritage algorithms have been leveraged from prior space vehicle designs. An overview of the Dream Chaser general vehicle capabilities including flight envelope, control authority and flight dynamics characteristics are presented. Finally, a summary of EDL integrated GN&C performance for the CRS-2 mission is presented via Monte Carlo analysis. [View Full Paper]

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AAS 20-078

INTERNATIONAL SPACE STATION DEORBIT CONTROLLABILITY ANALYSIS

Elisabeth A. Gambone*

An analysis was completed to determine the performance of the International Space Station (ISS) attitude control system in preparation for and during the final deorbit burn to decommission the ISS. A simulation was designed to calculate the minimum controllable altitude and altitude decay per day while using the Control Moment Gyroscope (CMG) Momentum Manager attitude control logic. A simulation was then designed to calculate the altitude decay and propellant usage per day while using the propulsive Reaction Control System below the minimum controllable altitude for CMGs. Finally, a simulation was designed to calculate the propellant usage for attitude control during the final deorbit burn. The Space Station Multiple Rigid Body Simulation (SSMRBS) was used for this analysis. The ISS flight software had to be modified to perform the deorbit burn using the desired thruster configuration. The analysis shows how controllability is maintained throughout altitude decay and the final deorbit burn with the current ISS mass properties. This analysis will be used to design nominal and contingency procedures to deorbit ISS into an uninhabited part of the ocean. [View Full Paper]

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ASTEROID EXPLORATION/
SMALL BODY SAMPLE RETURN

Session 8

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The following paper was not available for publication:

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AAS 20-089 to -090

AAS 20-081

EVOLVING DESIGN AND MOBILITY OF A SPACECRAFT ON STILTS TO EXPLORE ASTEROIDS

Himangshu Kalita,[*] Felicity Aldava,[†] Erik Asphaug[‡] and Jekan Thangavelautham[§]

Exploration of asteroids and comets will help to answer fundamental questions about the origins of the solar system. There are estimated to be nearly 2 million asteroid and comets in the solar system, and they are strategic locations for planetary science, planetary defense/security and for resource mining. Landing on these small bodies and manipulating their surface remains a major technical challenge fraught with high risk. The low gravity and low cohesive forces holding dust, gravel, and boulders together could result in surface ranging from 'quick-sand' to a hard gravel surface. The latest asteroid missions such as Hayabusa II and OSIRIS-REx will perform touch and go operations to mitigate the risks of 'landing' on an asteroid. Beyond these missions, there is an important need to perform surface and subsurface sampling from multiple points on an asteroid. The SPIKE (Spacecraft Penetrator for Increasing Knowledge of NEOs) spacecraft architecture is unique in that it is a hybrid combination of an orbiter and lander. The spacecraft extends out a low-mass, high-strength boom that has a series of in-situ instruments at the tip to sample the surface and subsurface of the asteroid from a distance. In this paper, we extended the design of the SPIKE spacecraft concept into two booms with each boom consisting of three revolute joints. By utilizing the latest advances in automated computer design the trajectories of each joint are optimized such that the spacecraft can perform multiple hops and walks on an asteroid surface. There however remain uncertainties with the asteroid surface material, hardness and overall risk posture on the mission. Using this proposed design, we attempted to refine our preliminary landing system. The proposed spacecraft design and controls approach is a major departure from conventional spacecraft with amphibious capabilities of a lander and orbiter vehicle packaged in one.

[View Full Paper]

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AAS 20-082

POLYHEDRAL SHAPE FROM SILHOUETTES FOR SMALL BODY CHARACTERIZATION

Paolo Panicucci,[*†‡] Jérémy Lebreton,[§] Jay McMahon,[**] Emmanuel Zenou[††] and Michel Delpech[‡‡]

Small bodies exploration highlighted the need to develop new algorithms for deep space probes navigation. The limited knowledge of small bodies properties imposes numerous challenges in mission design and spacecraft operation. In particular, the time required for communication and the uncertainty on small body parameters estimation require the development and improvement of autonomous navigation and decision making.

The estimation of the shape and rotation pole orientation in the inertial space is a crucial step for relative navigation and orbital frames definition, and an important milestone to investigate the gravity field under the assumption of constant density. Current techniques rely on shape from shadowing, i.e. stereophotoclinometry, or shape from motion, i.e. stereophotogrammetry. These approaches have been used since the beginning of asteroid exploration and, as a consequence, they have a high degree of reliability. Unfortunately, these algorithms cannot be used on board because of the extreme computational burden and the need of human-in-the-loop to control the convergence of the output solution. In the perspective of designing autonomous algorithms to enable navigation during the approach phase of small body missions, new solutions must be developed by limiting the needed data to the information available on board and by considering simpler algorithms that could be used without delayed communication with Earth.

This paper develops a shape from silhouette algorithm that takes as input a series of polygonal silhouettes to construct a polyhedral shape. The shape is computed by intersecting the viewing cones, i.e. the cone defined by having the camera center as vertex and the silhouette points as part of the edges. The algorithm output is a polyhedral shape that can be used for preliminary gravitational characterization of the small body, under hypothesis of constant density, or in model-based tracking algorithms.

Finally, numerical simulations are presented and commented to have an overview of the proposed algorithm. [View Full Paper]

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AAS 20-083

A COVARIANCE STUDY FOR GRAVITY ESTIMATION OF BINARY ASTEROIDS

Alex B. Davis* **and Daniel J. Scheeres†**

In support of future missions to binary asteroids, such as the proposed ESA HERA mission, we develop a covariance analysis framework for navigation of spacecraft about binary asteroid systems. Our dynamics model assumes the restricted full three body problem (RF3BP), a dynamical model in which a massless spacecraft or particle orbits two arbitrary asymmetric mass distributions, in this case asteroids. Because of their irregular shapes, the gravitational effect of the asteroids on one another and the spacecraft are modelled using a Legendre polynomial expansion of their mass distribution, described by the inertia integrals of each body. Within this dynamical model we develop the state transition matrix (STM) for the full system state as well as the mass parameter sensitivity matrix (MPSM) which linearly maps uncertainty in the mass parameters into the full system state. With this tool set we perform a series of consider covariance analyses to better understand estimation of the mass parameters of binary asteroid systems. We perform our study for 65803 Didymos, the binary target of the DART and HERA missions. [View Full Paper]

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AAS 20-084

STRATEGIES AND FLIGHT RESULTS OF GNC SYSTEM IN HAYABUSA2 TOUCHDOWN OPERATIONS: ARTIFICIAL LANDMARK "TARGET MARKER" SEPARATION AND ACQUISITION

Go Ono,[*] Hitoshi Ikeda,[†] Naoko Ogawa,[‡] Shota Kikuchi,[§] Fuyuto Terui,[**] Takanao Saiki[††] and Yuichi Tsuda[‡‡]

Hayabusa2 is a Japanese sample return mission from the near-Earth asteroid Ryugu. The spacecraft performed a touchdown operation successfully for the second time in February 2019 to sample pristine materials near an artificial crater created with an impactor. Since the surface of Ryugu was rough and full of boulders, accuracy requirements to guidance, navigation and control systems were demanding. In this paper, an overview of the systems is presented. Flight results prove that the performance of the systems was satisfactory and largely contributed to the success of the operation. [View Full Paper]

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STRATEGIES AND FLIGHT RESULTS OF GNC SYSTEM IN HAYABUSA2 TOUCHDOWN OPERATIONS: AUTONOMOUS SIX DEGREE OF FREEDOM CONTROL AFTER "TARGET MARKER" ACQUISITION

Fuyuto Terui,[*] Naoko Ogawa,[†] Shota Kikuchi,[‡] Go Ono,[§] Seiji Yasuda,[**] Tetsuya Masuda,[††] Kota Matsushima,[‡‡] Takanao Saiki[§§] and Yuichi Tsuda[***]

Hayabusa2 is a Japanese sample return mission from the asteroid Ryugu. The Hayabusa2 spacecraft was launched on 3 December 2014 and arrived at Ryugu on 27 June 2018. It had stayed there until December 2019 for in situ observation and soil sample collection, will return to the Earth in November or December 2020. During the stay, the spacecraft performed the first touchdown operation on 22nd of February 2019 and the second touchdown on 11th of July 2019 both successfully. The objective of the second touchdown operation was to sample pristine materials from beneath the surface of the asteroid. In April 2019, the spacecraft deployed SCI (Small Carry-on Impactor) and formed a crater. Although sampling sited within the crater itself were too rocky, an area with distance of 20 m from the crater center was identified and selected as a target for the second touchdown. Since the surface of Ryugu was rough and full of boulders, and safe area for touch-down was limited. The targeted area named "C01-Cb" had a radius of only 3.5 m, and the accuracy required to the guidance, navigation and control (GNC) of the spacecraft was challenging. This paper focuses on GNC strategy and flight data of the 2nd touchdown especially for the final descent phase after TM acquisition. [View Full Paper]

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IMAGE CORRELATION PERFORMANCE PREDICTION FOR AUTONOMOUS NAVIGATION OF OSIRIS-REX ASTEROID SAMPLE COLLECTION[*]

Courtney Mario,[†] Chris Norman,[‡] Eric Palmer,[§] John Weirich,[**] Curtis Miller,[‡] David A. Lorenz,[††] Ryan Olds[‡‡] and Dante S. Lauretta[§§]

Natural Feature Tracking (NFT) is an optical-based system that will provide autonomous state updates during Touch-And-Go (TAG) for the OSIRIS-REx asteroid sample collection. NFT operates by correlating onboard camera images with features rendered from an asteroid shape model built using science data from earlier mission phases. For these features to be correctly identified in the onboard camera images, NFT features must be defined from areas with unique terrain and built from a shape model that accurately models that terrain. As a result, NFT's overall performance is heavily dependent on this feature selection process and resulting feature models. Another challenge is that the viewing geometry of images during TAG will be different than that of most of the science images available for testing features prior to TAG. This paper will provide analysis of on-orbit feature performance from the NFT checkout, explore the feature selection process, and show analysis metrics that have been developed to ensure robust and well-modeled features are selected. In addition, this paper will explore ongoing analysis efforts to characterize how feature correlation performance for science images predicts what feature performance will be for images during TAG. Finally, this paper will explore how these methods are being used in preparation for sample collection to ensure NFT's overall success. [View Full Paper]

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AAS 20-088

REVISITING OSIRIS-REX TOUCH-AND-GO (TAG) PERFORMANCE GIVEN THE REALITIES OF ASTEROID BENNU

Kevin Berry,[*] Kenneth Getzandanner,[*] Michael Moreau,[*] Peter Antreasian,[†] Anjani Polit,[‡] Michael Nolan,[‡] Heather Enos[‡] and Dante Lauretta[‡]

The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) mission is a NASA New Frontiers mission that launched in 2016 and rendezvoused with the near-Earth asteroid (101955) Bennu in late 2018. Upon arrival, the surface of Bennu was found to be much rockier than expected.[1] The original Touch-and-Go (TAG) requirement for sample collection was to deliver the spacecraft to a site with a 25-meter radius;[2] however, the largest hazard-free sites are no larger than 8 meters in radius. To accommodate the dearth of safe sample collection sites, the project re-evaluated all aspects of flight system performance pertaining to TAG in order to account for the demonstrated performance of the spacecraft and navigation prediction accuracies. Moreover, the project has baselined onboard natural feature tracking[3] instead of lidar for providing the onboard navigation state update during the TAG sequence. This paper summarizes the improvements in error source estimation, enhancements in onboard trajectory correction, and results of recent Monte Carlo simulation to enable sample collection with the given constraints. TAG delivery and onboard navigation performance are presented for the final four candidate TAG sites. [View Full Paper]

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SYSTEMS ENGINEERING IMPACTS ON GN&C DESIGN

Session 9

National Chairpersons:

Bill Frazier, NASA Jet Propulsion Laboratory

Paul Graven, Cateni

Local Chairpersons:

Michael Osborne, Lockheed Martin Space Systems Company

Cody Allard, Ball Aerospace

The following paper numbers were not assigned:

AAS 20-097 to -100

AAS 20-091

SIMULATION-BASED ANALYSIS AND PREDICTION OF THRUST VECTOR SERVOELASTIC COUPLING

Jeb S. Orr,* John H. Wall† and Timothy M. Barrows‡

A method of analysis and prediction of servoelastic coupling in launch vehicles is presented, surveying the discovery and subsequent resolution of a predicted servoelastic resonance phenomenon affecting the NASA Space Launch System launch vehicle at specific flight conditions. A physics-based linearized multibody mechanization of the governing equations is combined with first principles analysis to demonstrate that antisymmetric bending of the solid rocket motors leads to a reduction of equivalent viscous modal damping through coupling with the thrust vector control actuators. The sensitivity to parameters and the effects of the resonance phenomenon on flight control performance and stability are confirmed through extensive simulation verification in the time and frequency domain. A novel enhancement in model fidelity that accounts for Coriolis effects of fluid flow on bending within the solid rocket motor case and nozzle is shown to add sufficient damping to reduce the risk of adverse control-structure interaction. [View Full Paper]

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AAS 20-092

HARDWARE VERIFICATION AND VALIDATION FOR A NAVIGATION SENSOR SOFTWARE MODEL IN SUPPORT OF FLIGHT VEHICLE PERFORMANCE ANALYSIS

Evan J. Anzalone,[*] Nicholas Hoen,[†] Thomas Park[‡] and Charles Weyandt[§]

… or, "It's in the details, how to make complicated software perform like complicated hardware." In attempts to minimize development time and quickly build an operational vehicle, NASA's Space Launch System (SLS) has had to be intentional about integrated testing. Constraints on budget and schedule have required balance between testing needs and the desire for an integrated flight vehicle as soon as possible. To provide key insights early in design and analysis cycles, a large amount of effort has shifted into maturing and validating models at the component level with integrated testing as a means to validate their integration. In terms of SLS Navigation, this, and the model-based design approach have pushed explicit requirements for sensor models to be validated against flight hardware to high precision. This paper covers the approach taken to verify and validate the models for the two key navigation sensors on the SLS vehicle, the Redundant Inertial Navigation Sensor and the Rate Gyro Assembly. These models are used in performance evaluation, fault detection, and operations development extensively. Using a mix of data from hardware vendor documentation and testing reports, limited in-house testing, and integration activities, these models were able to be validated against flight hardware at multiple levels, from the internal software design to statistical behavior at the raw sensor and integrated box levels. The high level of insight into the hardware elements is instrumental to support flight certification activities and building confidence in SLS Navigation capability. Focused testing enabled additional insight and validation that proved invaluable and the resulting insights were used to focus and mature models. Additionally, of having validated performance-based hardware models enables a wide breadth of activities including detailed fault detection studies and integration into future vehicle frameworks, such as an upper stage and provide a valuable asset to continued SLS analysis and design. [View Full Paper]

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AAS 20-093

SYSTEM DESIGN FOR NEAR-GLOBAL IMAGING OF TRITON

William Frazier,* Dustin Putnam,† Rebecca Schindhelm† and Michael Veto†

We propose a near-term low-cost mission to perform imaging of over 80% of the surface of Neptune's moon Triton during a single flyby. To accomplish this, we take advantage of Triton's 141 hr orbit period and design narrow-angle and wide-angle cameras to image over the wide range of distances and lighting conditions. Of particular interest in this paper is the process for high-resolution imaging as the range to the surface comes toward closest approach. To perform this, we traded a time-delay integration camera design with a slew-and-settle full-frame imager, and decided on the latter implementation. This required a high-performance attitude control system to cover the full disk in the allotted time, so a number of mosaic designs were iterated with simulated ADCS capabilities until a system design was established that showed appropriate margins. This paper describes the system design, including mission design summary, camera design summary, mosaicking pattern options, timelines, and detailed ADCS performance simulations showing slew and settle and pointing stability. [View Full Paper]

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AAS 20-094

DREAM CHASER® SPACEPLANE THRUSTER FAULT DETECTION, ISOLATION, AND RECOVERY ALGORITHM DESIGN DURING BREAKOUT MANEUVERS*

Remus C. Avram,† Christopher F. Ruswick† and Michael E. Trevino†

The Dream Chaser is a lifting body vehicle designed by Sierra Nevada Corporation capable of reaching and transporting cargo into low-Earth orbit, such as to the International Space Station (ISS). While in proximity to the ISS, the Dream Chaser must safely breakout in the presence of up to two system faults. This paper presents a fault detection, isolation, and recovery (FDIR) algorithm, which is able to satisfy stringent breakout performance requirements in the presence of multiple thruster faults. The successful execution of a breakout maneuver, in the presence of specific thruster faults relies partially on effectively identifying the failed thruster. A nonlinear, model-based approach is employed in the design of thruster FDIR algorithms. Specifically, a nonlinear fault detection estimator is designed to monitor in real time for the occurrences of thruster failures. Residuals generated by the nonlinear fault detection algorithm are used to identify the failed thruster and remove it from use. The effectiveness of thruster FDIR algorithms and breakout maneuver is demonstrated via simulation for a select number of critical cases. [View Full Paper]

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AAS 20-095

LINEAR COVARIANCE NAVIGATION ANALYSIS FOR AUTONOMOUS LUNAR LANDER MISSIONS

Randall Christensen,[*] David Geller[†] and Michael Hansen[‡]

Recently-proposed missions to the lunar surface have illustrated the need for precise, autonomous landing of spacecraft. The rapid drift of inertial navigation and the sparse availability of navigation aids near the moon have motivated alternative approaches to achieve the desired landing dispersions. Terrain-relative navigation exploits the appearance and structure of the lunar surface, and is capable of low navigation errors, without the need for additional measurements. This paper presents the development of a linear covariance framework for the analysis of a vision-based, terrain-relative navigation system during a powered lunar decent mission. Utilizing the developed framework, this research analyzes the performance and sensitivities of the proposed navigation system. Error budgets illustrate the contributions of each source of error from de-orbit insertion to touchdown. Sensitivity analyses are also performed to determine the effects of camera measurement availability and frequency. The results illustrate the need for a high resolution map that contains the landing site, which substantially reduces the horizontal components of position and velocity errors. Vertical errors, however, remain large with a vision-only navigation system, emphasizing the need for range-to-surface measurements. Error budget analyses also show that the dominant sources of error at touchdown comprise the star tracker, inertial measurement unit, and terrain camera measurement errors. [View Full Paper]

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AAS 20-096

LAUNCHER STRUCTURAL DYNAMICS AND CONTROL INTEGRATED DESIGN

Martine Ganet,* Valentin Pothier* and Vincent Le Gallo*

System engineering requires tools to manage the trade-offs as soon as possible in the next generation launcher design process. Among these trades-off, one of the most critical one is the reduction of the structural index of the launcher by reducing the stiffness constraints while still being able to control the flexible dynamics. In this study, the co-design method has been implemented to search for the minimal admissible structural parameters (damping coefficient and natural frequency) of the first flexible mode of a launcher, while maintaining the launcher controller performance (stability, performance and robustness). This method was successfully applied to an Ariane study case allowing reducing significantly the structural index. [View Full Paper]

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EXPLORING MARS

Session 10

National Chairpersons:

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Andrew Johnson, NASA Jet Propulsion Laboratory

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Jorgen Baertsch, Left Hand Design Corp

Zach Yearout, Left Hand Design Corp

The following paper numbers were not assigned:

AAS 20-107 to -110

AAS 20-101

MARS 2020 AUTONOMOUS ROVER NAVIGATION*

Michael McHenry,† Neil Abcouwer, Jeffrey Biesiadecki, Johnny Chang, Tyler Del Sesto, Andrew Johnson, Todd Litwin, Mark Maimone, Jack Morrison,‡ Richard Rieber, Olivier Toupet, Philip Twu

Rovers have been critical elements of Mars Exploration, beginning with Sojourner in 1997, Spirit and Opportunity in 2004, and most recently the Mars Science Laboratory's Curiosity rover, which has now traveled more than 23 km since its landing in 2012. In the summer of 2020, NASA and the Jet Propulsion Laboratory (JPL) will launch the Mars 2020 rover with the goal of acquiring curated samples from Mars for possible return to Earth by a future mission. While the mobility mechanisms are inherited from the MSL rover, a number of significant technological advancements to software and avionics were made in order to meet mission objectives. In this paper, we present the most significant improvements in the area of Autonomous Rover Navigation, specifically:

- Use of the Vision Compute Element (an FPGA-equipped co-processor) to accelerate image processing.
- Software changes to enable image and navigation processing to occur in parallel with vehicle motion.
- A new path-planner algorithm named "Enhanced Nav" enabling autonomous drives in more challenging terrains than Curiosity can traverse.

[View Full Paper]

* This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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AAS 20-102

ESCAPE, PLASMA AND ACCELERATION DYNAMICS EXPLORERS (ESCAPADE)

Jeffrey S. Parker,[*] Nathan Parrish,[†]
Robert Lillis,[‡] Shannon Curry[§] and David Curtis[**]

The Escape, Plasma and Acceleration Dynamics Explorers (ESCAPADE) mission will provide a comprehensive picture of how solar wind energy flows through Mars' unique hybrid magnetosphere to drive ion and sputtering escape. This paper examines ESCAPADE's mission design at a high level, surveying each phase of the transfer from launch through the end of the primary science mission at Mars. ESCAPADE launches as a secondary with Psyche and uses solar electric propulsion and aerobraking to achieve the mission. ESCAPADE has two science campaigns: the first involves both spacecraft being in the same orbit in a string-of-pearls configuration; the second involves both spacecraft traversing very different plasma regions about Mars.

[View Full Paper]

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AAS 20-103

AVIONICS HARDWARE MODELING AND EMBEDDED FLIGHT SOFTWARE TESTING IN AN EMULATED FLAT-SAT

Mar Cols Margenet,[*] Hanspeter Schaub[†] and Scott Piggott[‡]

This manuscript describes the end-to-end flight software (FSW) development process for an interplanetary spacecraft mission in which the University of Colorado Boulder and the Laboratory for Atmospheric and Space Physics are collaborating. As the term "end-to-end" indicates, the entire FSW development cycle is covered: starting from a preliminary desktop design and analysis all the way to testing on the flight hardware. For desktop prototyping, the strategy of using Python as a wrapper for C/C++ flight algorithm code is employed. The Basilisk software testbed is presented as a specific incarnation of this desktop development strategy. For embedded development, this work uses the Core Flight System (CFS) middleware and the same C flight algorithm developed in the desktop environment. Regarding flight hardware, a flat-sat emulation is utilized to perform embedded testing of the resulting CFS-FSW application. The flat-sat is emulated in the sense that all the different mission components are software models replicating its hardware counterparts. Here, the CFS-FSW application runs within a processor board emulator and interacts with external applications like the spacecraft physical simulation and a ground system model. Numerical simulation results showcase the closed-loop performance of the embedded CFS-FSW application in an interplanetary mission scenario. [View Full Paper]

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AAS 20-104

ALTITUDE CONTROL OF A SOLAR BALLOON FOR MARS EXPLORATION

Tristan Schuler,[*] Sergey Shkarayev[†] and Jekan Thangavelautham[*]

Exploration of Mars has been made possible using a series of increasingly sophisticated landers, rovers and orbiters. These three options for exploration have operated for prolonged periods lasting months to years. However, due to limitations in landing technology, it is still not possible to access the rugged environments on Mars, particularly regions such as Valles Marineris, the southern highlands or the northern and southern poles. A solar balloon is a credible solution to accessing aerial imagery and performing science missions in previously hard to reach areas. Solar balloons are also heated naturally by the sun and don't require an external tank of gas for initial inflation. The present work analyzes the feasibility of solar balloons on Mars. The work presents an in-depth model for altitude control of a solar balloon and altitude controllability in the Martian atmosphere. [View Full Paper]

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THE MARS 2020 LANDER VISION SYSTEM FIELD TEST

A. Johnson, N. Villaume, C. Umsted, A. Kourchians, D. Sternberg, N. Trawny, Y. Cheng, E. Geipel and J. Montgomery*

The Mars 2020 Lander Vision System estimates position relative to an on-board map and provides this information to the spacecraft so that large hazards can be avoided during landing. The LVS is a new mission critical sensor and as such requires extensive validation. A field test conducted in May 2019 was the primary means to prove that the LVS will operate as designed. During this test over 600 independent real-time runs on engineering model LVS hardware and software were executed and clearly showed that it could meet a 40m position estimation requirement over a wide operational envelope. This paper will describe the test approach, operations and results. Specific examples as well as aggregate performance will be discussed along with off-nominal testing and fault recovery. [View Full Paper]

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CHALLENGES OF MARS SAMPLE RETURN LANDER ENTRY, DESCENT, AND LANDING

Mark C. Ivanov*and Steven W. Sell†

The proposed Mars Sample Return (MSR) campaign would be perhaps the most ambitious robotic mission ever attempted in space exploration. The notional campaign consists of three Flagship-class missions operating in cooperation for over a decade in order to return samples of the Martian surface and atmosphere to Earth for analysis. The Mars 2020 rover, scheduled to launch in July 2020, will cache samples and place them on the surface for possible return. The second mission would be a Sample Return Lander (SRL) that consists of a small Sample Fetch Rover (SFR) to gather the samples, a Sample Transfer Arm (STA) to load the samples into a Mars Ascent Vehicle (MAV), and the MAV itself to launch the samples into orbit around Mars. The third mission would be an Earth Return Orbiter (ERO) designed to rendezvous and capture the Orbiting Sample (OS), return to Earth, and separate the Earth Entry Vehicle (EEV) for Entry, Descent, and Landing (EDL) at a location to be determined. This paper will focus on the SRL mission concept, specifically the EDL phase. Given the ambitious SRL sample retrieval baseline surface mission, including a rocket launch of the samples into Mars orbit, it is estimated that the EDL system may be required to deliver as much as 2100 kg of dry mass to the surface. This represents an approximate 20-25% increase in mass capability over previous landed Mars missions. Additionally, there is a high probability that SRL would have to land very close to the samples on the surface to expedite retrieval operations; therefore, Pin Point Landing (PPL) accuracy may be required. To address these challenges, promising EDL configuration augmentations were studied to include larger forebody/higher drag entry capsules, hypersonic/supersonic inflatable/non-inflatable aerodynamic decelerators, hypersonic trim tabs, ballute drag devices, larger parachutes, higher Mach and higher dynamic pressure parachute deployments, lower parachute deployment altitudes that have shorter chute timelines that necessitate more efficient terrain sensor strategies, and additional fuel for longer powered descent diverts to the target landing site. Overarching the entire trade study was an attempt to stay as close to the experience base of past successful missions as possible to reduce implementation cost and risk. This paper will discuss the entire SRL EDL trade study in detail. The information presented about the potential MSR campaign is pre-decisional and is provided for planning and discussion purposes only. [View Full Paper]

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GENERAL ADVANCES IN GUIDANCE AND CONTROL

Session 11

National Chairpersons:

Tim Crain, Intuitive Machines

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Local Chairpersons:

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Drew Engelmann, Laboratory for Atmospheric Space and Physics

The following paper was not available for publication:

AAS 20-111 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 20-119 to -120

AAS 20-112

MODELING EFFECTIVE CONTROL OF SATELLITE OSCILLATIONS USING A FINITE ELEMENT METHOD

Ryotaro Sakamoto* and Daniel J. Scheeres†

The control of a spacecraft with oscillations is developed and its effectiveness is discussed based on feedback control theory and finite element methods (FEM). Spacecraft oscillations are caused by several factors, such as solar radiation pressure (SRP), engine noise, and actuator noise, among others. These oscillations adversely affect the activity of spacecraft. For example, these oscillations degrade the accuracy of deployable array antennas, which need to be kept pointed precisely.[1] In order to stabilize models against these oscillations, effective control methods are evaluated considering attenuation. A number of technical issues are involved in designing control law and implement for flexible structures. One of them is the effect of sensor and actuator locations. It might be a better control design to implement as many sensors and actuators as the number of multiple degrees of freedom. However, this approach is neither practical nor cost effective.

In this study, the satellite flexure dynamics are based on the damping equation with mass, stiffness matrix, and an excitation force. Oscillation is simulated by a simple sinusoidal function as an excitation force. Forced vibration is applied to one point of model to cause system oscillation. Two finite element models are used to study typical spacecrafts. One model is a simple plate model. Another has a body component and two symmetric panels. These three dimensional models are simulating a simple body component and solar array panels. In this work, the degree of freedom of one node is defined by six components, which are x, y, and z directions and the angles between them. By doing modal analysis of these model, the resonance frequencies and deformation shape can be obtained. Identifying critical nodes is important to design an effective control law.

Feedback control is designed by linear quadratic regulation (LQR) and the Ricatti equation as a full state feedback system.3 Control is modeled as a torque at each node. These nodes are simulated as hinge or ball joints of the solar array. The critical node, to which control should be applied, is found via modal analysis and tuning of elements of R matrix. By leveraging the deformation information to tune Q and R matrices, effective control is established. Total energy of the models and cost from LQR theory are evaluated as performance results. These methods can be used to develop better control approaches for non-uniformly rotating satellites in addition to the control of oscillating satellites. [View Full Paper]

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AAS 20-113

CHARACTERIZATION OF PLANETARY RESOURCES WITH DEEP LEARNING ENABLED MODEL PREDICTIVE CONTROL: APPLIED TO LUNAR ICE MAPPING

Michael Lieber,[*] Reuben Rohrschneider,[†] Zachary Britt,[‡]
Rebecca Schindhelm[§] and Jonathan Weinberg[**]

The drive toward more cost-effective space missions has been enabled by recent technology advancements in areas of component miniaturization, and computational advances in throughput with increased onboard memory. As the level of autonomous operation increases, the data collection process can be optimized and adapted to a time-varying scene – sometimes called data driven control. One approach to architecting an optimal control system with multiple constraints and a time-varying environment (or scene) is to leverage technology already being developed for complex, ground-based (or air-based) systems. The model predictive control (MPC) architecture, with a layered hierarchical structure has been found to provide a promising framework for achieving control under complex, and un-certain environments.[1,2,3] Unlike conventional control algorithms, MPC predicts ahead over a finite time horizon and then re-computes an optimal set of commands at every time-step.

For this paper, we discuss simulation and lab results with a real-time scene classifier used to control an adaptive, multi-beam lidar for selective ground illumination. Due to the large computational load imposed by MPC, we then replace the on-board scene classifier (simulation only) with a deep learning-based algorithm and apply this technology to a proposed application characterizing/ mapping recently identified water ice[4,5] in lunar crater shadows. For the precise reason that lunar ice exists in the permanently shadowed regions (PSR), also makes it extremely difficult to detect and characterize this essential resource for human habitation and exploration, as it appears as a very dark to any passive sensor. [View Full Paper]

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AAS 20-114

OPTICAL WAVEFRONT ERROR ESTIMATION ALGORITHM USING TEMPERATURE MEASUREMENTS FOR SEGMENTED SPACE TELESCOPES

Joel Runnels,[*] Cody Allard[*] and J. Scott Knight[†]

The observation CONOPs for the James Webb Space Telescope (Webb) requires the observatory to stay within a certain level of optical stability between control updates. The major driver of the optical stability is the thermal stability of the observatory. If Webb does not meet the required optical stability due to a thermal short or undesirable thermal gradients and transients, a modification to the nominal observation CONOPs and optical control strategy may be required. This research introduces an optical wavefront error estimation algorithm which uses the attitude of the spacecraft and temperature measurements and estimates the current and future thermal and optical wavefront error states of the system. The results from the algorithm developed in this paper show that the wave front error estimator yields 10% error. These results are promising considering the non-linear and complex thermo-elastic dynamics of the system driving the optical states. These states could be fed into an optical controller which could allow the system to meet the optical stability requirements while minimizing the control updates. [View Full Paper]

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AAS 20-115

LYAPUNOV GUIDANCE IN ORBIT ELEMENT SPACE FOR LOW-THRUST CISLUNAR TRAJECTORIES

Joseph T. A. Peterson,[*] Sandeep K. Singh,[*] John L. Junkins[†] and Ehsan Taheri[‡]

Lyapunov methods are well established as a versatile approach for generating feasible and robustly converging spiral-type low-thrust trajectories. The present study introduces Lyapunov optimal methods for low-thrust guidance. The approach makes use of the regularized modified equinoctial orbit elements in such a way that a nominal trajectory can be tracked, even with large starting deviations. When the deviations are large, the method amounts to a tracking law generalization of existing orbit transfer approaches. In such cases, the local thrust is chosen to maximize the local rate of decrease of a Lyapunov function that measures the time-varying departure of the actual trajectory from the desired, where each trajectory is represented by osculating equinoctial elements. The chattering phenomenon in the neighborhood of the nominal trajectory is avoided by smoothly throttling the allowable control bound in such a way that asymptotic convergence to the trajectory is achieved in the absence of navigation errors. In the presence of navigation errors, the covariance of tracking errors can be used to define a deadband region near the nominal trajectory where control is set to zero. This permits coasting unless departure motion exits the navigation accuracy deadband. The proposed approach is applied to two segments of a multi-month low-thrust mission to demonstrate that the approach can accommodate rather bland cislunar dynamics as well as precise convergence to a target low lunar orbit. [View Full Paper]

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AAS 20-116

DREAM CHASER® SPACEPLANE DEORBIT BURN GUIDANCE ALGORITHM AND FUEL EFFICIENCY ANALYSIS*

Begum Cannataro,† David A. Benson,‡ Stephen Thrasher,§ Louis Breger and Ernest E. Lagimoniere Jr.††**

The Dream Chaser spaceplane deorbit burn guidance algorithm is explained. The fixed delta-velocity deorbit burn performance is evaluated in two reference frames: the Earth-centered-inertial (ECI) reference frame and the local-vertical-local-horizontal (LVLH) reference frame. Although the deorbit burn fixed in LVLH is more efficient than the deorbit burn fixed in ECI, LVLH deorbit burn is more sensitive to acceleration uncertainties than ECI deorbit burn. The de-orbit burn is also evaluated using two different jet select strategies: pseudo-Dv and off-pulsing. The pseudo-Dv strategy combines multiple translation jets to fire together to simulate one jet and requires additional jet firings to balance residual moments and maintain attitude. Off-pulsing fires multiple translation jets and periodically turns off a subset of the jets to maintain attitude. The pseudo-Dv strategy provides a constant level of acceleration but results in higher propellant consumption relative to off-pulsing, whereas off-pulsing is more efficient than the pseudo-Dv, the achieved acceleration is inconsistent and sensitive to uncertainties in the center of gravity.

[View Full Paper]

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AAS 20-117

DEEP ON-BOARD SCHEDULING FOR AUTONOMOUS ATTITUDE GUIDANCE OPERATIONS

Andrew Harris[*] and Hanspeter Schaub[†]

Increasingly complex space missions have motivated the development of autonomous mission guidance approaches capable of dealing with high-dimensional, continuous observation and action spaces. Deep reinforcement learning (DRL) techniques are a rising area of research for dealing with such problems, but at present lack clear methods for verification or validation, especially in the context of spacecraft operations. This work identifies a specific problem architecture for addressing a high-level attitude mode guidance problem on-board through the use of a pre-trained learning agent using contemporary strategies for safety and verification from the deep learning community. Additionally, high-performance, open-source space-specific simulation tools derived from the AVS Basilisk astrodynamics simulation package are presented and discussed. The resulting end-to-end development and verification pipeline is presented against other approaches and compared on the basis of accuracy, computational efficiency, and safety. [View Full Paper]

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AAS 20-118

A GENERALIZED GUIDANCE APPROACH TO IN-SPACE SOLID-PROPELLANT VEHICLE MANEUVERS

Jason M. Everett*

Exploration-class vehicles that require fully autonomous ascent and descent must employ robust, explicit path-adaptive guidance algorithms that can operate in a wide range of physical environments. Vehicle designs that employ solid-propellant rocket motors (SRMs) for maneuvers are attractive from a systems engineering perspective because of their simplicity and reliability, but may cause complications for both mission designers and GNC engineers when dealing with total impulse uncertainty, as well as proper energy management of a motor with an uncontrolled cutoff time. This paper presents a simplified guidance algorithm, named Simple Cross-Product Steering (SxS), that was derived during early studies of NASA's Mars Sample Return mission's Mars Ascent Vehicle. The algorithm takes roots in a flight-proven guidance algorithm commonly referred to as Cross-Product Steering. SxS has been shown to provide sufficient guidance accuracy for in-space SRM burns in a simulated Martian environment, and preliminary studies have been conducted to test the algorithm in a solid-propellant lunar braking scenario. A method for predicting proper motor ignition time during execution of the Cross-Product Steering algorithm is the primary contribution of this paper. Mechanization notes are also provided that were realized in early phases of MAV. Results are shown for an example ascent vehicle in a simulated Mars environment. [View Full Paper]

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ADVANCES IN NAVIGATION

Session 12

National Chairpersons:

John Christian, Rensselaer Polytechnic Institute

Shyam Bhaskaran, NASA Jet Propulsion Laboratory

Local Chairpersons:

Siamak Hesar, Blue Canyon Technology

Morgan Yost, Lockheed Martin Space Systems Company

The following paper numbers were not assigned:

AAS 20-129 to -130

AAS 20-121

SIMULTANEOUS AND DISTINCT VISIBLE AND THERMAL RADIATION PRESSURE DYNAMICS

Scott J. K. Carnahan[*] and Hanspeter Schaub[†]

This work modifies previously published methods to evaluate solar radiation pressure (SRP) and thermal radiation pressure (TRP) dynamic effects on a spacecraft and extends these models to incorporate self-emitted TRP. The modifications delineate effects due to visible-band and thermal-band radiation. With these methods, the independent effects of thermal and visible spectrum radiation on spacecraft orbits can be analyzed using only a small number of coefficients. The effects captured include dynamics due to visible and thermal solar radiation, earth albedo, earth infrared radiation, and spacecraft thermal emissions. Spacecraft thermal control systems rely on surface finishes with specified solar absorptance and thermal emittance coefficients. These coefficients couple the spacecraft thermal design with spacecraft dynamics via radiation pressure. This work analyzes that coupling by closely examining how the application of the coefficients in the visible and thermal spectral bands affects orbit propagation. Finally, numerical modeling tools are developed that allow for the analysis of thermo-physical models of spacecraft tightly coupled to the spacecraft dynamics and environment. Together, the work here forms the basis for the analysis of the full, spectral analysis of radiation pressure on spacecraft trajectories.

[View Full Paper]

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AAS 20-122

EUROPA-CLIPPER STELLAR REFERENCE UNIT FILTERING TECHNIQUES FOR PROCESSING OPTICAL OBSERVATIONS

Yannick Henriquel, Matthieu Beaumel, Laurent Nicollet, Benoit Gelin,[*]

Gabrielle Massone, James Alexander and Herrick Chang[†]

This paper presents the techniques that have been implemented on the Europa Clipper Star Tracker to operate in the high radiation environment of Europa, a Moon of Jupiter. [View Full Paper]

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AAS 20-123

GUIDE STAR SELECTION FOR SPACECRAFT NAVIGATION WITH STARNAV

William Parker,[*] Ryan Thibeault,[*] Grace Quintero[*] and John Christian[†]

Recent investigation into using the relativistic perturbation of starlight for spacecraft navigation has shown that a vehicle's velocity can be estimated from observing a change in apparent inter-star angles due to stellar aberration. However, only a subset of observable stars are suitable for use as navigation guide stars, and the characteristics of a star (type, size, brightness, direction, proper motion, etc.) play a role in determining its suitability. This paper outlines a process for selecting candidate stars which are ideal for navigation by stellar aberration, then details theoretical mission scenarios utilizing these candidate stars as a proof of concept. [View Full Paper]

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AAS 20-124

SATELLITE NAVIGATION USING X-RAY PULSARS AND HORIZON CROSSINGS OF X-RAY STARS

Kent S. Wood,[*] Paul S. Ray,[†] Michael T. Wolff,[‡] Keith Gendreau,[§]

Zaven Arzoumanian,[**] Jason W. Mitchell[††] and Luke M. B. Winternitz[‡‡]

A previous report (Mitchell *et al.*, AAS 18-155)) described X-ray navigation using X-ray pulsars in a mode analogous to GPS, and a flight demonstration called SEXTANT employing the Neutron Star Interior and Composition Explorer (NICER) as the X-ray detector system. This talk describes using the same instrument in a different mode, to observe horizon-crossings of X-ray stars and then extract navigational information from those transitions. The two techniques can be combined for more effective X-ray navigation near planets, for example in low earth orbit.

[View Full Paper]

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AAS 20-125

OPTICAL NAVIGATION FOR AUTONOMOUS APPROACH OF UNEXPLORED SMALL BODIES

Jacopo Villa,[*] Saptarshi Bandyopadhyay,[†] Benjamin Morrell,[†] Benjamin Hockman,[†] Daniel Lubey,[†] Alexei Harvard,[‡] Soon-Jo Chung,[‡] Shyam Bhaskaran[†] and Issa A. Nesnas[†]

State of the practice in navigation toward and around small celestial bodies heavily relies on ground support and human skill, in particular, for perception-based operations such as optical navigation and mapping. This leads to longer and more complex mission operations and subsequently higher cost. Furthermore, it imposes limitations for certain missions such as fast fly-bys or multi-agent operations. In this work, we present an autonomous navigation strategy for approaching small unexplored bodies. During the approach, we estimate the body's physical properties as well as the spacecraft relative trajectory and associated uncertainties. The autonomous navigation strategy, which is solely based on optical measurements, begins as soon as the body becomes resolved in the navigation camera and terminates at the start of proximity operations, when the spacecraft makes its first trajectory correction to stay in the vicinity of the body. Our multi-phased approach uses light-curve analysis for estimating the body's rotation rate, Shape-from-Silhouette techniques to reconstruct the 3D shape and estimating its rotation pole, and feature tracking tailored to small-body images for estimating relative navigation parameters. We used the Mission Analysis, Operations, and Navigation Toolkit Environment (MONTE), developed by the Jet Propulsion Laboratory and simulated images to evaluate the feasibility and performance of the algorithms. As a case study, we reproduce the approach phase of the Rosetta mission. This work is based on the assumptions that the spacecraft attitude is known, the body is a principal-axis rotator, and a-priori estimates of ephemerides and scale are available. Preliminary results show orbit determination performance that is on par with human navigation from the Rosetta mission; albeit a bias in spacecraft position estimate is observed. This systematic error is likely due to the correlation among feature detection and dynamic lighting conditions and perspective changes.

[View Full Paper]

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AUTONOMOUS ON-ORBIT OPTICAL NAVIGATION TECHNIQUES FOR ROBUST POSE-ESTIMATION

Thibaud Teil,[*] Samuel Bateman[†] and Hanspeter Schaub[‡]

This paper seeks to improve image acquisition and processing methods through the use of Neural Networks. Flight Software algorithms must be developed for robust onboard use as these algorithms interact heavily with the space environment. Testing them reliably therefore requires high-fidelity and computationally fast simulations that allow simulated crafts to navigate visually. Raw camera images are often noisy, imperfect, and contain artifacts. Therefore, modeling images requires knowledge of the environment and of the camera. A fast and reliable OpNav simulation opens the door to training Convolutional Neural Networks as it can provide numerous images paired with truth data. The caveat being that both the training environment and the resulting neural network need to be tested and vetted to ensure applicability to real missions.

The proposed research will focus on navigation in proximity to known celestial bodies rather than in a deep space cruise. The scenario used is a spacecraft on orbit around Mars. In this situation, the baseline method for orbit determination is based on Center and Apparent Diameter (CAD) measurements. The primary goal of this research is to assess the accuracy of existing methods and compare them to new Neural Networks pre-trained in the Basilisk-Vizard environment. The results demonstrate the ability for neural network based image processing for space applications and display the robustness of the navigation solution. [View Full Paper]

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AAS 20-127

SMART NAV TARGETING ALGORITHM FOR THE DART MISSION

Peter Ericksen,[*] Stephen Jenkins,[†] Mark Jensenius[‡] and Michelle Chen[§]

A previous paper (AAS 18-063) at the 2018 AAS GNC Conference introduced the small-body maneuvering autonomous real-time navigation (SMART Nav) concept for the NASA Double Asteroid Redirection Test (DART). In order to demonstrate the kinetic impactor approach to asteroid deflection, the mission re-quires autonomous targeting, guidance, and optical navigation during the terminal phase to ensure impact with Didymos B of the Didymos binary asteroid system. This paper will focus in-depth on the updated design of the targeting algorithm, which ingests blob centroids processed from imagery and provides line of sight estimates for Didymos A and Didymos B to the guidance filter. The performance of the targeting algorithm and robustness to known mission uncertainties and plausible spacecraft faults will be demonstrated with results from analysis activities using our increasingly high fidelity DARTSim closed loop spacecraft simulation in tandem with our renderer and camera emulator (RCE) that generates simulated payload imagery. [View Full Paper]

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AAS 20-128

THIN VPU: OPEN SOURCE VISION PROCESSING FOR SPACE NAVIGATION

Shaun Stewart,[*] Giovanni Molina[†] and Tim Crain[‡]

Intuitive Machines (IM) is developing a vision processing system for precision landing and hazard avoidance on the Nova-C lander for the IM-1 mission landing on the Moon in 2021. The vision processing system supports terrain relative navigation, hazard map generation, landing site selection, and hazard relative navigation. A key component of the IM vision processing architecture is a hardware/software appliance named "ThinVPU" dedicated to handling the most common vision processing functions needed for space applications. IM is developing the ThinVPU in conjunction with a NASA Tipping Point project with a commercialization model aimed at reducing the cost and schedule required for deploying optical navigation capabilities on future commercial and exploration space missions. The ThinVPU will use open source algorithms and software on a space qualified processor with a standard software application interface. IM will validate the ThinVPU software with archived and synthetic imagery for space applications and then verify the performance of the combined software and space-qualified hardware appliance in a hardware-in-the-loop test environment. Ultimately, the ThinVPU hardware architecture, associated flight software and validation data will be made available open-source with the objective of reducing the cost of vision based navigation system development for future space missions. This paper will introduce the ThinVPU concept within the IM vision processing architecture, present the commercialization model and development plan for the open-source architecture, and provide preliminary IM-1 navigation analysis of the possibilities of optical navigation motivating the development of the ThinVPU. [View Full Paper]

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ADVANCES IN SOFTWARE

Session 13

National Chairpersons:

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Blair Thompson, Aleut Management Services

Local Chairpersons:

Scott Piggott, Laboratory for Atmospheric and Space Physics

Tomas Ryan, Ball Aerospace

The following paper was not available for publication:

AAS 20-133 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 20-139 to -140

AAS 20-131

COMPACT FRAME INDEPENDENT SPACECRAFT DYNAMICS DEVELOPMENT USING SYMPY PYTHON LIBRARY

Cody Allard[*] and Drew Engelmann[†]

Developing the rotational and translational equations of motion for spacecraft can be a time consuming, error prone, and complex task. In particular, when the rigid body assumption can no longer be used due to additional degrees of freedom flexible structures, or other non rigid-body effects the derivation can become laborsome. One solution to solve this problem is to use a symbolic toolbox from a software package to carry out the mathematics. However, most symbolic toolboxes require the user to define matrices using matrix components and therefore cannot perform frame independent vector and tensor calculus. This method yields lengthy equations that are difficult to manage, and the desired compact frame independent vector/tensor solution is lost. SymPy, an open source Python library, enables the user to perform vector calculus allowing for the desired solution to be found. However, there are some limitations with this method because the package requires the use of basis vectors when defining any vector or inertia tensor. This paper provides example derivations of a simple two link pendulum system and a complex spacecraft dynamics problem using SymPy and shows the power of utilizing this tool. [View Full Paper]

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AAS 20-132

EFFECT OF SPACECRAFT PARAMETERS ON IDENTIFICATION OF DEBRIS STRIKES IN GN&C TELEMETRY

Anne Aryadne Bennett[*†] and Hanspeter Schaub[‡]

Debris strikes on operational spacecraft are becoming more common due to increasing numbers of space objects. Sample return missions indicate hundreds of minor strikes, but rigorous analysis is often only performed when a strike causes an anomaly in spacecraft performance. Developing techniques to identify and assess minor strikes that do not immediately cause anomalous behavior can help to validate models for debris populations, perform risk assessments, and aid in attribution of future anomalies. This study uses a spacecraft dynamics simulation to determine the effects of minor debris strikes as observed in attitude control system (ACS) telemetry. A variety of filters are applied to a range of ACS telemetry points to identify subtle strikes in noisy telemetry. A series of trades is conducted to examine the effects of spacecraft parameters on strike detectability and assessment accuracy. Traded parameters include spacecraft size, telemetry rate, and telemetry noise. The results from these trades are presented and the implications for the strike detection and assessment capabilities of spacecraft are discussed. [View Full Paper]

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A NEW MESSAGING SYSTEM FOR BASILISK

Scott J. K. Carnahan,* Scott Piggott† and Hanspeter Schaub‡

The Basilisk Astrodynamics Framework utilizes a messaging system to specify and implement interfaces between spacecraft simulation modules. A new messaging system has been developed for the Basilisk Astrodynamics Framework to enable or better enable multiple-spacecraft simulations, multi-threaded simulations, dynamically allocated message payloads, message connection by users, and message type-checking. Templated C++ functor classes are used for message read and write operations, providing direct but controlled access to message memory. Memory-safe and bit-for-bit repeatable multi-threaded simulations are also enabled by the functor implementation. [View Full Paper]

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AAS 20-135

SEMI-ANALYTIC METHOD FOR REPEAT GROUND TRACK ORBIT DESIGN

Blair F. Thompson* **and Aaron C. Brogley***

We present a novel method for the design and maintenance of repeat ground track (RGT) orbits. The primary objective of the method is to constrain the terminal points of the orbit track to be the same point in Earth-fixed space after one track period, which subsequently results in the desired repeat ground track. A separate but similar method has been developed for the design of sun-synchronous RGT orbits. The track repeat period and number of orbits in the track are user-defined variable design parameters. Inclination is user-defined only for standard RGT orbits (i.e., not sun-synchronous orbits). The method begins with a nominal two-body orbit at some desired ascending node and epoch time. Analytic techniques of general perturbations are applied to modify the orbit into a frozen orbit with low-order gravitational perturbations. The method continues by numerically integrating the orbit in the Earth-centered inertial (ECI) frame with persistent, higher-order gravity perturbations and a fast *regula falsi* root finder to arrive precisely at the perturbed ascending node of the subsequent orbit. The orbital elements are altered at the end of the precision nodal period to compensate for any east-west precession of the ascending node due to the perturbations. The altered orbit is numerically integrated over the entire repeat track period using higher-order persistent perturbations. The terminal miss distance and direction are used to differentially correct the initial conditions to force the orbit to end at the same point at which it started in Earth-fixed space. Once the final repeat ground track orbit has been determined, Earth-fixed waypoints along the orbit track are generated for use during orbit maintenance.

[View Full Paper]

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PYTHON SCIENTIFIC PROGRAMMING TOOL SUITE FOR ANALYSIS AND VERIFICATION OF ARTEMIS-1 NAVIGATION SYSTEM

Brandon Wood*

Analysis of spacecraft test and verification data has historically involved large and diverse data sets processed with a variety of ad-hoc tools. For Artemis-1, the challenge of working with large test and verification data sets paired with the volume of Monte Carlo simulations presented the need for an efficient frame-work for engineers to load, process, and analyze the results. Verification, Evaluation of Requirements, Analysis, and Synthesis (VERAS) is a Python scientific programming tool suite developed by Orion GN&C engineers for statistical analysis of large data sets, automated requirement verification, and report generation. The VERAS framework is object-oriented by design which promotes modularity of analysis and verification objects and reuse of code through inheritance of abstract classes. The Orion Navigation team developed VERAS objects applicable to both Monte Carlo simulation and asynchronous laboratory test data sets. The objects were used to evaluate navigation state accuracy requirements, identify and diagnose simulation and flight software defects, assess navigation filter performance, and inform flight rule development. VERAS enabled successful verification of the navigation system across all phases of the Artemis-1 mission. [View Full Paper]

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AAS 20-137

VALIDATION OF THE LAGUERRE METHOD FOR SOLVING THE 8TH ORDER POLYNOMIAL OF ANGLES-ONLY INITIAL ORBIT DETERMINATION

Ryan Cobb*[*] and Blair F. Thompson[†]

We present the results of a validation study of the Laguerre root-finding method for application to angles-only initial orbit determination (IOD). The Laplace and Gauss methods both process the minimal six observation angles to generate an initial orbit state. Both methods require determination of the correct real root of an 8th order polynomial. Typically, additional observations are used to eliminate spurious roots by generating an independent solution with partially common observations – the root that appears in both solutions is the correct root. The simple and computationally quick Laguerre root-finding method is well suited to be embedded in angles-only IOD software in lieu of more complex root finding routines, especially in autonomous flight software where computational processing power and speed are often very limited. However, the Laguerre method computes a single root of the polynomial, and that root might not be the correct, desired root. In this paper we present the results of a study of the suitability of the Laguerre method for determining the correct root with no additional a priori information. This capability would improve the efficiency and autonomy of both methods, making them more effective for space surveillance, space situational awareness, and other applications. To that end, the primary goal of our analysis was to address two questions: 1) Is the largest real root always the correct real root? and 2) Does the Laguerre method always compute the largest real root? We do not offer a rigorous mathematical proof to answer either question (although we do not dispute that such a proof may exist). Instead, we use a Monte Carlo-type approach to determine with a high level of certainty if the Laguerre method always produces the correct root for a statistically significant number of test cases covering a variety of orbit types and initial estimates. From randomized initial orbits we generate simulated angles-only observations, then process the observations using the Laguerre root-finder for both the Laplace and Gauss polynomials. The results are validated against the known orbits to determine if the Laguerre method computes the correct root. The validation results ascertain whether the Laguerre method can routinely provide consistent, accurate results, and the effectiveness of the Laguerre method for angles-only initial orbit determination is assessed. After a large set of test cases, it is determined that the Laguerre method does not help in determining the correct root from a three-root case. [View Full Paper]

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AAS 20-138

OPTIMAL RELATIVE TRAJECTORY DESIGN WITH MISSION CONSTRAINTS AND PERFORMANCE REQUIREMENTS

Nathan B. Stastny,[*] David K. Geller[†] and Simon Shuster[‡]

This paper briefly discusses several current RPO trajectory planning techniques and their applicability to constrained operations. Several key real-world planning constraints and their impact to operations are identified. A new trajectory planning approach is then presented that seeks a stochastically optimal trajectory that meets mission constraints while also accounting for vehicle performance. This approach combines a closed-loop linear covariance (LinCov) simulation of the relative trajectory with a genetic algorithm (GA) to determine the optimal trajectory. Several example scenarios are evaluated for an RPO spacecraft that employs angles-only navigation to perform multi-burn trajectory transfers around a resident space object (RSO). Vehicle performance parameters include navigation uncertainties and actuator control errors. A final state dispersion constraint is also applied. Performance of the stochastically optimal trajectory is compared to the performance of other optimization techniques through the LinCov simulation. [View Full Paper]

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AUTONOMOUS RPOD, SERVICING, COLLISION AVOIDANCE AND DEBRIS REMOVAL

Session 14

National Chairpersons:

Tim Payne, USSF S3/6Z

Apoorua Bhopale, Air Force Research Laboratory

Local Chairpersons:

Cheryl Walker, Parsons

David Chart, Sierra Nevada Corp

The following paper numbers were not assigned:

AAS 20-149 to -150

AAS 20-141

RENDEZVOUS AND PROXIMITY OPERATIONS FOR ACTIVE DEBRIS REMOVAL SATELLITES CONSIDERING TRAJECTORY SAFETY

Takahiro Sasaki,[*] Yu Nakajima[*] and Toru Yamamoto[†]

As the amount of debris in orbit increases, so do the risks and seriousness of collisions. All nations having or planning space operations acknowledge this growing threat. One possible solution receiving more and more attention is the active debris removal (ADR) mission. The first step in such a mission would be for the removal satellite to approach the debris. In such case, it is important to ensure passive abort (PA) safety, which is needed in the event of sensor or actuator failure, and guarantee the robustness to collisions due to off-nominal thruster burn, since a non-cooperative target lacks all navigation aids such as laser reflectors or markers to support reliable relative navigation. This paper compares two candidate trajectories–the V-bar hopping and spiral approaches–by considering the ΔV budget, duration of operation, and robustness against collisions, and also compares two candidate orbits at the proximity hold point for precise motion estimation of the debris. From the comparison of these two candidate trajectories and two holding orbits, this paper then proposes the spiral-based nominal trajectory with small variation in the line-of-sight (LoS) vector, which enables the ease of the satellite's system design regarding power control, thermal maintenance, and communications. Through the numerical example, the effectiveness of the proposed trajectory is demonstrated. [View Full Paper]

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AAS 20-142

AN ANALYTIC GUIDANCE LAW FOR SAFETY ELLIPSE RECONFIGURATIONS

Simon Shuster[*] and David Geller[†]

This paper presents a closed-form guidance law that reconfigures safety ellipses. Safety ellipses are relative motion trajectories that do not require thrusting to ensure a high probability of short-term collision avoidance. The reconfigurations considered in this paper are resizing, or changing the dimensions of the safety ellipse, and phasing, or changing the spacecraft's location along the safety ellipse. The guidance law computes a three-impulse maneuver sequence with burns separated by a half orbit period. For nominal reconfiguration scenarios, primer vector theory is used to relate optimality to properties of the initial and final safety ellipses. The primer vector analysis is validated numerically. For off-nominal reconfiguration scenarios, Monte Carlo methods are used to analyze the optimality of the guidance law. [View Full Paper]

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SUB-MINIMUM IMPULSE ATTITUDE/RATE CONTROL OF SPACECRAFT

John P. McCullough, III,* Steven L. Hough,†
Keith R. Clements‡ and Robert A. Hall§

In one of the future NASA exploration missions utilizing the Space Launch System (SLS), the Orion spacecraft separates from the Exploration Upper Stage (EUS), reorients itself end over end, and then autonomously or manually docks with a Co-manifested Payload (CPL) that is attached to the forward end of the EUS. During Rendezvous, Proximity Operations, and Docking (RPOD), the mated EUS/CPL acts as the passive vehicle for docking, yet must actively minimize body rates and translational velocity at the docking interface to accommodate International Docking System Standard (IDSS) requirements and more stringent Orion manual docking handling qualities. The initially designed EUS closed loop autopilot (i.e., flex filters, classically based phase plane, etc.) with the vehicle's mass properties and its baseline, twelve, non-throttle-able hydrazine thruster configuration is insufficient for achieving the initial docking state allocations.

Subsequently, more complex control modes are developed and analyzed to help minimize rates at the docking interface. These software modes include a minimum impulse mode, a feed forward state estimator mode, and a sub-minimum impulse mode. Monte Carlo analyses results are shown for these cases to illustrate the time domain performance in dispersed conditions for anticipated mission objectives. The sub-minimum impulse algorithm provides the lowest body rates of the analyzed control modes, and is the only one that meets the initial al-locations.

Refinements to the RPOD requirements for the impacted missions allows several of the algorithms to robustly achieve increased docking rate allocations. Therefore, the sub-minimum impulse is not needed for the baseline design. However, sub-minimum impulse shows promise where further reductions in body rates are desired for a particular vehicle configuration, with only a modest impact to complexity over the standard autopilot design. [View Full Paper]

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AAS 20-144

AUTONOMOUS DEPLOYMENT OF PAYLOAD PACKAGES TO SPINNING ROCKET BODIES: APPROACH, APPARATUS, AND EMULATION USING GROUND ROBOTICS

Caleb Peck,[*] Davis W. Adams,[*] James McElreath,[*] Andrew Verras,[*] Joe Hiemerl,[†] Manoranjan Majji,[‡] Moble Benedict[§] and John Junkins[**]

An innovative approach to identify the rotation rate of a tumbling rigid and autonomously deploy a payload package is presented in this paper. The experimental prototype of a delivery system, including the sensor system, and computational vision algorithms for identification of the deployment site and the ground robots at the Land, Air and Space Robotics (LASR) laboratory, Texas A & M University used for validation experiments are detailed. Various component subsystems are discussed, and the integration of the systems to realize the guidance, navigation and control (GN & C) package to accomplish the proximity operations with spinning bodies is detailed, along with lessons learned. [View Full Paper]

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AAS 20-145

DESIGN OF SAFE ABORT CORRIDORS FOR *DREAM CHASER*® SPACEPLANE

Christopher Jewison,[*] David Benson,[*] Louis Breger[*]
Chris Ruswick[†] and Ernest E. Lagimoniere Jr.[†]

Safety is paramount when operating a spacecraft in close proximity to the International Space Station (ISS). In a scenario where the safety of a mission is compromised, the spacecraft must be able to abort its planned trajectory. To preserve the safety of the mission, any viable breakout maneuver must also be performed without further endangering the ISS. This paper discusses the method used to de-fine a corridor where Dream Chaser can safely abort its rendezvous. Because of the need to be able to execute a breakout at any moment, this corridor also defines the region in which the spacecraft can safely operate. If the spacecraft approaches the edge of this corridor, it must immediately perform a breakout. The corridor is given in the form of linear constraints on the relative position and velocity of the vehicles. Dispersion results from a Monte Carlo simulation are used to inform choices in the corridor definition for different phases of the mission. Both a polytope propagation with linear reachability analysis and vertex propagation with a nonlinear simulation are used to verify that the defined corridors meet all safety requirements when a breakout maneuver is carried out. These methods are discussed with example analysis results from the Dream Chaser program. [View Full Paper]

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AAS 20-146

OPTIMAL LOW THRUST ORBIT TRANSFERS FOR SPACE TELESCOPE REFUELING AT SEL2

Robyn M. Woollands* **and Siegfried Eggl†‡**

The James Webb Space Telescope (JWST), a ten billion-dollar infrared telescope with a 6.5m primary mirror to be launched in 2021, is designed to operate in a Halo orbit around the second Sun-Earth Lagrange point (SEL2) for five to ten years. At that point fuel for station keeping and attitude maneuvers will run out. Refueling missions to JWST, as well as to similar space telescope missions proposed for SEL2, could greatly enhance the "science-per-dollar" value and promote a more sustainable use of space assets. In this paper, we present a novel approach to designing fuel optimal trajectories that will allow the refueling spacecraft to arrive at the SEL2 Halo orbit with maximum final mass (i.e. fuel payload). The low thrust optimal control problem is formulated using an indirect optimization method, leading to a two-point boundary value problem with a bang-bang control structure. We make use of a hyperbolic tangent smoothing technique for performing continuation on the thrust magnitude to reduce the sharpness of the control switches in early iterations and, thus, promote convergence. The problem is posed and solved in the circular restricted three-body problem. In this dynamical system, invariant manifolds exist that can be utilized to reduce fuel consumption. The here presented methodology to this challenging and important problem in astrodynamics demonstrates a significant potential for low-cost refueling mission design. [View Full Paper]

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AAS 20-147

MODELING, CONTROL AND LABORATORY TESTING OF AN ELECTROMAGNETIC DOCKING SYSTEM FOR SMALL SATELLITES

Aaditya Ravindran,[*] Leonard D. Vance[†] and Jekanthan Thangavelautham[‡]

Small-satellites and CubeSats offer a low-cost pathway to perform technology demonstrations in space, deploy instruments for earth observation and perform exploration. Small-spacecrafts and CubeSats have the potential to be modules that can be constructed into large structures and observatories in space. This would require small-spacecraft and CubeSats to have mechanisms to dock. Such an approach avoids high-risk due to a single launch failure or loss of an individual craft. The CubeSat or small-spacecraft modules maybe stockpiled from many launches. Various docking mechanisms like the Power Data Grapple Fixture (PDGF) on the ISS and the Soyuz docking system have been developed. Small satellite docking mechanisms are just emerging. This paper proposes development of a general purpose electromagnetic docking mechanism. This electromagnetic docking mechanism is an example of a nonlinear system. The dynamics of the system is modeled. Using this dynamics model, various controllers have been designed. The selected controller has a distance-controlled feedback loop to perform docking. A preliminary mission concept to test the docking mechanism and the docking controller has been proposed and discussed. A prototype of a docking system is evaluated in the laboratory and discussed in the paper. [View Full Paper]

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AAS 20-148

FLASH LIDAR ON-ORBIT PERFORMANCE AT ASTEROID BENNU*

Estelle C. A. Church,† Tyler Bourbeau,‡ James Curriden,‡ Angelica M. Deguzman,§ Frank J. Jaen, Huikang Ma,§ Keith M. Mahoney,†† Curtis J. Miller,§ Brad Short,‡ Kristian I. Waldorff,†† Oliver K. Walthall†† and Dante S. Lauretta‡‡**

NASA's Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) spacecraft is currently orbiting asteroid (101955) Bennu with the ultimate goal of collecting a sample from the asteroid's surface and returning it to Earth. After launching from Cape Canaveral Air Force Station in September 2016, the OSIRIS-REx spacecraft travelled for nearly two years before arriving at asteroid Bennu in December 2018. Before entering orbit around Bennu, the spacecraft conducted a series of detailed surface scans. At the time, this achievement marked the closest orbit of a planetary body by a spacecraft, approximately 1.3 km, and set the record for Bennu as the smallest body ever orbited. Surveillance of Bennu continued in preparation for selecting a site to collect a regolith sample from the surface. The flash LIDAR is one of the navigation sensors for the Touch and Go (TAG) event. Several checkouts of the instrument were performed in flight including lasing at the surface of Bennu to verify its performance. Analyzing the LIDAR data over the asteroid surface against the shape model produced range data well within accuracy requirements. The LIDAR has performed nominally in flight as the first flash LIDAR used in a deep space mission. There has been no degradation to the laser and sensor, and no optical alignment issues have been observed. [View Full Paper]

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RECENT EXPERIENCES IN GUIDANCE, NAVIGATION AND CONTROL

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David Dannemiller, NASA Johnson Space Center

Islam Hussein, Thornton Tomasetti

Local Chairpersons:

Kip Gwin, Ball Aerospace

Cody Griffin, Sierra Nevada Corp

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AAS 20-155 (Paper Withdrawn)

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AAS 20-151

TRAJECTORY DESIGN AND MANEUVER PERFORMANCE OF THE OSIRIS-REX DETAILED SURVEY OF BENNU

Daniel R. Wibben,[*] Andrew Levine,[*] Samantha Rieger,[†] James V. McAdams,[*] Kenneth M. Getzandanner,[†] Peter G. Antreasian,[*] Jason M. Leonard,[*] Michael C. Moreau[†] and Dante S. Lauretta[‡]

OSIRIS-REx has now spent over a year at target asteroid Bennu and has completed its Site Selection Campaign—a period of time dedicated to fully mapping Bennu in order to determine the best possible location to touchdown and collect a sample from the asteroid's surface. This paper describes the trajectory design of the first phase of this campaign: Detailed Survey. The trajectory design will be discussed starting from the assessment of all science objectives and will summarize the performance of all executed maneuvers, which enabled collection of critical data products vital for sample site selection. [View Full Paper]

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AAS 20-152

ORION ASCENT ABORT-2 NAVIGATION SYSTEM IMPLEMENTATION AND POST-FLIGHT ASSESSMENT

Emily Kollin[*]

In July 2019, NASA flew the Orion Ascent Abort-2 (AA-2) flight test, successfully demonstrating the ability of the Launch Abort System (LAS) to safely steer the Crew Module (CM) away from a launch vehicle in the event of an emergency during ascent. The AA-2 CM's navigation system was a key contributor to test success, as it was the source of navigation data used by the CM's guidance and control algorithms to provide the LAS Attitude Control Motor (ACM) with thrust commands to execute during the abort. Although the CM article flown for AA-2 was an emulator of the mainline Artemis CM, it was required that its on-board guidance, navigation, and control (GN&C) software be the same as that to be used for future Artemis missions. Therefore, several measures were taken to accommodate the mainline navigation software in the different AA-2 environment. During the rigorous AA-2 test campaigns, various issues with the potential to negatively impact navigation system performance were identified, analyzed, and, as necessary, remedied. The navigation system performance during the AA-2 flight test proves the efficacy of the mainline CM navigation software and its ability to navigate well during ascent, even under the stressing conditions of an abort environment, ensuring crew safety for the future Artemis missions. [View Full Paper]

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OSIRIS-REX SHAPE MODEL PERFORMANCE DURING THE NAVIGATION CAMPAIGN

Jason M. Leonard,[*] Jeroen L. Geeraert,[*] Brian R. Page,[*] Andrew S. French,[*] Benjamin W. Ashman,[†] Peter G. Antreasian,[*] Coralie Adam,[*] Erik Lessac-Chenen,[*] Leilah McCarthy,[*] Derek Nelson,[*] John Pelgrift,[*] Eric Sahr,[*] Andrew Liounis,[†] Eric Palmer,[‡] John R. Weirich,[‡] Brian M. Kennedy,[§] Nickolaos Mastrodemos,[§] Julie Bellerose,[§] Daniel Lubey,[§] Brian Rush,[§] Dianna Velez,[§] Michael C. Moreau,[†] Olivier Barnouin[**] and Dante S. Lauretta[††]

The Navigation Campaign of the OSIRIS-REx mission began when the first image of Bennu was recorded by the PolyCam high-resolution imager on August 17, 2018. In the ensuing months, two teams began building shape models based on imagery taken during the Approach and Preliminary Survey phases to be used for the transition to landmark navigation in the Orbital A phase. The orbit determination team began analyzing and characterizing the performance and errors associated with each shape model delivery, working closely to iterate on the next shape model delivery. By the end of Orbital A, shape models produced by the Altimetry Working Group and JPL exceeded pre-launch performance requirements. This paper provides a summary of the analysis performed during operations. [View Full Paper]

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AAS 20-154

ON-ORBIT EVALUATION OF NATURAL FEATURE TRACKING FOR OSIRIS-REX SAMPLE COLLECTION[*]

Curtis Miller,[†] Ryan Olds,[‡] Chris Norman,[†] Sierra Gonzales,[§] Courtney Mario[**] and Dante S. Lauretta[††]

The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) mission employs an autonomous optical-based orbit determination capability for navigating to the surface of asteroid Bennu to enable collection of a regolith sample. This navigation system, known as Natural Feature Tracking (NFT), was specifically developed for OSIRIS-REx and had no in-flight heritage. This system utilizes the natural terrain to perform onboard autonomous navigation and is the first of its kind to be flown on an exploratory space mission. To gain confidence in the navigation solution of the NFT system prior to sample collection, a series of three orbital checkouts was performed. These checkouts consisted of NFT processing a series of images of Bennu while in a terminator orbit. The solution from NFT was compared to ground reconstruction of the orbit utilizing much higher-fidelity modeling. Using the telemetry from NFT and the trajectory comparison, the performance of NFT's algorithms and the quality of its inputs were evaluated. This paper will discuss the details of the checkouts, the calibrations and inputs that went into NFT, the performance of NFT's solutions, the implications of NFT's performance and quality of its inputs has on the sample collection, and forward work required to pre-pare NFT for sample collection. [View Full Paper]

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AAS 20-156

ON-ORBIT PERFORMANCE OF THE BCP-100 GREEN PROPELLANT INFUSION MISSION

Brian Marotta,[*] Christopher McLean[†] and Brad Porter[‡]

The Green Propellant Infusion Mission (GPIM) spacecraft was launched in June of 2019 as a secondary payload on the Air Force's STP-2 Falcon Heavy launch vehicle. GPIM is a BCP-100, a line of ESPA class spacecraft designed by Ball. The BCP-100 was designed around the capability to support multiple payloads on a single platform, and be able to fly in a wide range of orbits without the need to reconfigure the spacecraft in any way. Proving the flexibility and multi-role capability of the BCP-100 design, there are three secondary payloads on GPIM. In addition to the green propellant payload, iMESA, SWATS, and SOS are hosted on the spacecraft. These were provided by the Air Force through their Space Experiments Review Board (SERB) payload list. GPIM adds to the 15 years of combined flight time for the BCP-100 line.

Ball Aerospace built the GPIM spacecraft for NASA's Space Technology Mission Directorate (STMD) in order to provide a platform to accomplish on-orbit testing and validation of an AF-M315E based green propellant propulsion subsystem. After a very successful spacecraft commissioning phase that was completed in less than 24 hours, check out of the primary green propellant payload commenced. This included testing the primary and redundant catbed heaters, opening the latch valve, and commanding the thrusters in both open loop and closed loop control modes, all of which was accomplished within three and a half days of being on-orbit.

The propulsion system employs five protoflight 1 N thrusters, four for attitude control and the fifth for use during delta-v burns to provide higher thrust. Characterization of the green propellant system has been on-going. This characterization includes performing closed loop delta-v burns, 3-axis thruster-based attitude control, and momentum dumping. In addition to these tests, on-orbit measurement of the thruster impulse-bit has been performed over the course of the mission. This measurement involves a complex command sequence in which the spacecraft must execute a delta-v, perform multiple maneuvers, spin down the reaction wheels, and execute a series of 200 msec long open loop thruster pulses. Analysis of the spacecraft motion that results from each thruster pulse provides the amount of force that was applied.

This paper provides a brief background of the GPIM program, including objectives of the technology demonstration, and presents on-orbit flight results of propulsion tests performed to date.

[View Full Paper]

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AAS 20-157

THE VOYAGERS: RISKY BUSINESS BEYOND THE HELIOPAUSE

Bruce Waggoner* **and William Frazier***

Both 43 year old Voyager spacecraft have entered interstellar space while continuing to return exciting and unique scientific data. While it is possible that both spacecraft might operate until 2030, many components are presenting problems just as resource margins are eroding to critical levels. The flight team is managing risks to almost every significant subsystem on the vehicles and many of these risks are interconnected. This paper offers a summary of the major issues encounter by the flight team and how each problem is being managed. [View Full Paper]

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AAS 20-158

SEEKER FREE-FLYING INSPECTOR GNC FLIGHT PERFORMANCE

Samuel Pedrotty,[*] Jacob Sullivan,[*] Elisabeth Gambone[*] and Thomas Kirven[†]

Seeker is an automated extravehicular inspection spacecraft that was designed and built in-house at the NASA Johnson Space Center (JSC) over approximately 18 months with a budget of $1.8 million. This first version of Seeker is intended to be an incremental development towards an advanced inspection capability. Seeker launched onboard the NG-11 Cygnus mission in 2019 and deployed from Cygnus on September 16, 2019. Downlinked telemetry, imagery from the chaser (Seeker) and target (Cygnus) spacecraft, and onboard engineering data logs are used to provide an analysis of the system's performance. This paper reviews the performance of the Seeker vehicle with a focus on the guidance, navigation, and control (GNC) system. The results are presented with a discussion of the related system design to highlight how decisions and applied methods culminated in the observed performance. [View Full Paper]

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POSTER SESSION

Poster Session

AAS 20-161

SATELLITE DYNAMICS TOOLBOX FOR PRELIMINARY DESIGN PHASE

Daniel Alazard* **and Francesco Sanfedino†**

This paper presents the latest developments of the Satellite Dynamics Toolbox dedicated to the modeling of large flexible space structures. The satellite is considered as a flexible multi-body system with open or closed loop kinematics chains of flexible bodies. Each body (platform, reaction wheels, booms, antenna, solar panels, …) is modeled as a substructure in which each sizing parameters can be declared as a varying or uncertain parameter. The whole model is thus fully compatible with the MATLAB robust control toolbox to perform sensitivity analysis and pointing performance budget at the preliminary design phase level. [View Full Paper]

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AAS 20-162

MODELING OF AN ON-ORBIT MAINTENANCE ROBOTIC ARM TEST-BED

Jacob J. Korczyk,[*] Daniel Posada,[†] Francisco J. Franquiz,[‡] Madhur Tiwari[§] and Troy Henderson[**]

This paper focuses on the development of a ground based test-bed to analyze the complexities of contact dynamics between multibody systems in space. The test-bed consists of an air-bearing platform equipped with a 7 degrees-of-freedom (one degree per revolute joint) robotic arm which acts as the servicing satellite. A second arm, stationary with respect to the first, acts as the client spacecraft. The interactions between the arms and the platform are modeled as an aid for the analysis and design of stabilizing control algorithms suited for autonomous on-orbit servicing missions.

The dynamics are represented analytically using a recursive Newton-Euler multibody method with D-H parameters derived from the physical properties of the arm and platform. An independent numerical simulation created with the SimScape™ modeling environment is also presented as a means of verifying the accuracy of the recursive model. The results from both models are then validated through comparison with internal measurement data taken from the robotic arm itself.

[View Full Paper]

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AAS 20-163

MAGNETIC TORQUER BAR INTERACTIONS

Jim Krebs[*] and Eric Stromswold[†]

Magnetic Torquer Bars (MTBs) are electromagnetics. The torque generated by the interaction of their magnetic moment with the Earth's magnetic field helps control a satellite's attitude or orientation. The magnitude of the magnetic fields generated along the sides of the MTBs are on the order of ten gauss. The field magnitude generated at the two ends of the MTB are typically a kilogauss or more. These fields can magnetize nearby MTBs, thus generating undesired moments in unintended directions. To quantify these effects, Cayuga Astronautics (CA) has measured the parasitic moments generated by perpendicular and parallel MTB pairs. The MTB interactions were found to be smaller than typically assumed. Consequently, these results can be used by designers in the development of compact satellite buses. [View Full Paper]

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AAS 20-164

SPACECRAFT PROXIMITY NAVIGATION USING THE IVISNAV SENSOR SYSTEM

Kookjin Sung*[*] and Manoranjan Majji[†]

Technical details associated with a novel relative motion sensor system called the interferometric Vision Navigation (iVisNav) are elaborated in the paper. It is shown that by a unique combination of analog and digital photonic elements, it is possible to simultaneously estimate the relative pose of a cooperative target and the relative rates at different bandwidths. This is accomplished by simultaneously illuminating a digital CMOS sensor with low frequency modulations and an avalanche photodiode of the high frequency modulations of structured light beacons. Navigation filter developments associated with the iVisNav sensor are detailed. Sensor characteristics are studied to realize optimum performance of the navigation filters. Bench top prototype experiments are carried out in the Land, Air, and Space Robotics (LASR) laboratory at Texas A&M University show optimism towards the utility of the proposed technology for spacecraft proximity operation applications. [View Full Paper]

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* Unless otherwise indicated all papers appear in Volume 172, *Advances in the Astronautical Sciences*. Part I and Part II indicate in which part in the hard copy version of the proceedings that the paper appears.

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AAS 20-094 Dream Chaser® Spaceplane Thruster Fault Detection, Isolation, and Recovery Algorithm Design During Breakout Maneuvers, Remus C. Avram, Christopher F. Ruswick and Michael E. Trevino (Part II)

AAS 20-095 Linear Covariance Navigation Analysis for Autonomous Lunar Lander Missions, Randall Christensen, David Geller and Michael Hansen (Part II)

AAS 20-096 Launcher Structural Dynamics and Control Integrated Design, Martine Ganet, Valentin Pothier and Vincent Le Gallo (Part II)

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